FRAMATOME ANP

EMF-2328(NP)(A)
Revision 0

PWR Small Break LOCA Evaluation Model, S-RELAP5 Based

March 2001

Advanced Nuclear Power

Framatome ANP Richland, Inc.

Proprietary

Siemens Power Corporation

ISSUED IN FRA-ANP ON-LINE
DOCUMENT SYSTEM
DATE: 5/10/01

~~ISSUED IN SPC ON-LINE
DOCUMENT SYSTEM
DATE: 1-11-00~~

EMF-2328(NP)
Revision 0

PWR Small Break LOCA Evaluation Model, S-RELAP5 Based

Prepared: Kenneth E Carlson 1/10/00

K. E. Carlson, Staff Engineer
Safety Analysis Methods

Date

Contributors: H. Chow, S. E Jensen, A. B. Meginnis, W. T. Nutt, D. L. Caraher, W. S. Yeung

Concurred: James F. Mallay 1/10/00

J. F. Mallay, Director
Regulatory Affairs

Date

jap

U.S. Nuclear Regulatory Commission
Report Disclaimer

Important Notice Regarding Contents and Use of This Document

Please Read Carefully

This technical report was derived through research and development programs sponsored by Siemens Power Corporation. It is being submitted by Siemens Power Corporation to the U.S. Nuclear Regulatory Commission as part of a technical contribution to facilitate safety analyses by licensees of the U.S. Nuclear Regulatory Commission which utilize Siemens Power Corporation fabricated reload fuel or technical services provided by Siemens Power Corporation for light water power reactors and it is true and correct to the best of Siemens Power Corporation's knowledge, information, and belief. The information contained herein may be used by the U.S. Nuclear Regulatory Commission in its review of this report and, under the terms of the respective agreements, by licensees or applicants before the U.S. Nuclear Regulatory Commission which are customers of Siemens Power Corporation in their demonstration of compliance with the U.S. Nuclear Regulatory Commission's regulations.

Siemens Power Corporation's warranties and representations concerning the subject matter of this document are those set forth in the agreement between Siemens Power Corporation and the Customer pursuant to which this document is issued. Accordingly, except as otherwise expressly provided in such agreement, neither Siemens Power Corporation nor any person acting on its behalf:

a. makes any warranty, or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this document, or that the use of any information, apparatus, method, or process disclosed in this document will not infringe privately owned rights;

   or

b. assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this document.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

March 15, 2001

Mr. James F. Mallay
Director, Regulatory Affairs
Framatome ANP, Richland, Inc.
2101 Horn Rapids Road
Richland, WA 99352

SUBJECT: ACCEPTANCE FOR REFERENCING OF LICENSING TOPICAL REPORT EMF-2328(P), REVISION 0, "PWR SMALL BREAK LOCA EVALUATION MODEL, S-RELAP5 BASED" (TAC NO. MA8022)

Dear Mr. Mallay:

The NRC staff has completed its review of Topical Report EMF-2328(P), Revision 0, "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based" submitted by Framatome ANP Richland, Inc. (FRA-ANP) on January 10, 2000, and supplement dated January 26, 2001.

On the basis of our review, the staff finds the subject report to be acceptable for referencing in license applications to the extent specified, and under the limitations delineated in the report, and in the enclosed safety evaluation (SE). The SE defines the basis for NRC acceptance of the report.

The staff notes that a condition imposed on the use of the ANF-RELAP code still applies to the use of S-RELAP5. Specifically, that while it has been shown in NUREG/CR-4945, "Summary of the Semiscale Program (1965-1986)," that the thermal-hydraulic phenomena observed for breaks up to 10 percent of the cold leg flow area are the same, if the code is used for break sizes larger than 10 percent of the cold leg flow area additional assessments must be performed to ensure that the code is predicting the important phenomena which may occur.

Pursuant to 10 CFR 2.790, we have determined that the enclosed SE does not contain proprietary information. However, we will delay placing the SE in the public document room for a period of ten (10) working days from the date of this letter to provide you with the opportunity to comment on the proprietary aspects only. If you believe that any information in the enclosure is proprietary, please identify such information line by line and define the basis pursuant to the criteria of 10 CFR 2.790.

The staff will not repeat its review and acceptance of the matters described in the report, when the report appears as a reference in license applications, except to assure that the material presented is applicable to the specific plant involved. Our acceptance applies only to the matters described in the report.

In accordance with the procedures established in NUREG-0390, the NRC requests that FRA-ANP publish accepted versions of the report, including the safety evaluation, in the proprietary and non-proprietary forms within 3 months of receipt of this letter. The accepted versions shall incorporate this letter and the enclosed evaluation between the title page and the abstract. The accepted versions shall include an "-A" (designating accepted) following the report identification symbol. The accepted versions shall also incorporate all communications between FRA-ANP and the staff during this review.

Should our criteria or regulations change so that our conclusions as to the acceptability of the report are no longer valid, FRA-ANP and the licensees referencing the topical report will be expected to revise and resubmit their respective documentation, or to submit justification for the continued effective applicability of the topical report without revision of their respective documentation.

Sincerely,

Stuart A. Richards, Director
Project Directorate IV and Decommissioning
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Project No. 702

Enclosure: Safety Evaluation

UNITED STATES

NUCLEAR REGULATORY COMMISSION

WASHINGTON, D.C. 20555-0001

SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT EMF-2328(P), REVISION 0

"PWR SMALL BREAK LOCA EVALUATION MODEL, S-RELAP5 BASED"

FRAMATOME ANP, RICHLAND, INC.

PROJECT NO. 702

1.0 INTRODUCTION

Framatome ANP Richland, Inc. (FRA-ANP) submitted Topical Report EMF-2328(P), Revision 0, "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based," (Reference 1), for NRC review and approval for application of the S-RELAP5 thermal-hydraulic analysis computer code (Reference 2), to the small break loss-of-coolant accident (SBLOCA) in Westinghouse and Combustion Engineering pressurized water reactors (PWRs). FRA-ANP plans to replace the previously NRC-approved methodology using the ANF-RELAP and TOODEE2 codes for the SBLOCA analysis. The application submitted for review is under the guidelines of 10 CFR 50.46 and 10 CFR Part 50, Appendix K.

The stated goal of FRA-ANP is to apply a single computer code to the analysis of both LOCA and non-LOCA transient events. The code of choice is to be one that has had wide industry acceptance and application. To achieve this goal the decision was made to modify the approved ANF-RELAP code (References 3 and 4), in such a way as to bring it up to a standard that incorporates the thermal-hydraulic code RELAP5/MOD2 (Reference 5), the fuel design code RODEX2, (Reference 6), the ICECON containment model (Reference 7), and the hot rod model code TOODEE2, (Reference 8) into a single system calculation. In so doing, the RELAP5/MOD2 code was modified to include selected models from the RELAP5/MOD3 code, (Reference 9) improved numerics, and models necessary to satisfy the requirements of 10 CFR Part 50, Appendix K.

2.0 STAFF APPROACH TO REVIEW

The proposal to review S-RELAP5 was made by FRA-ANP to the staff on January 10, 2000 (Reference 10). The code documentation, including an electronic copy of the code, was reviewed for completeness and accepted for detailed review by the staff. The staff performed the review by assembling a team of five staff members with expertise in thermal-hydraulics, kinetics and RELAP5 use. The review emphasized those portions of the code which were different from the RELAP5/MOD2 and RELAP5/MOD3 codes since they have not had the same level of peer review as the models and correlations in the base codes. In addition, the staff felt it necessary to have confidence that the model additions, especially the numerical methodology changes, did not adversely alter the performance and stability of the code.

During the course of the review, a request for additional information (RAI) was developed and transmitted to FRA-ANP (Reference 11). Meetings were held with the Advisory Committee on Reactor Safeguards (ACRS) Thermal-Hydraulic Phenomena Subcommittee. Those meetings and reviews conducted by the ACRS members and their consultants were considered in preparation of the aforementioned RAI.

Milestones in the Review

- Request for review of S-RELAP5: January 10, 2000. Receipt of code and documentation: January 2000. Acceptance of code for review by NRC: March 2000.

- Request for additional information by the staff: December 2000.

- Advisory Committee on Reactor Safeguards, Thermal-Hydraulic Phenomena Subcommittee meetings: March 2000, August 2000, January 2001.

- Advisory Committee on Reactor Safeguards, Full Committee meeting: February 2001.

3.0 S-RELAP5 MODIFICATIONS AND ADDITIONS

The RELAP5 computer code is a light water reactor transient analysis code developed for the NRC for use in rulemaking, licensing audit calculations, evaluation of operator guidelines, and as a basis for nuclear power plant analyses. RELAP5 is a general purpose code that, in addition to calculating the behavior of a reactor coolant system during a transient, can be used for simulation of a wide variety of hydraulic and thermal transients in both nuclear and non-nuclear systems involving mixtures of steam, water, non-condensable gas, and solute. The RELAP5 code is based on a nonhomogeneous and nonequilibrium model for the two-phase system. Solution is by a partially implicit numerical scheme to permit economical calculation of system transients. The objective of the RELAP5 development effort was to produce a code that included important first-order effects necessary for accurate prediction of system transients but that was sufficiently simple and cost effective so that parametric or sensitivity studies were possible.

The code includes many generic component models from which general systems can be simulated. These component models include pumps, valves, pipes, heat releasing or absorbing structures, reactor point kinetics, electric heaters, jet pumps, turbines, separators, accumulators, and control and trip system components. In addition, special process models are included for effects such as form loss, flow at an abrupt area change, branching, choked flow, counter-current flow limiting (CCFL), boron tracking, and noncondensable gas transport. The code also incorporates many user conveniences such as extensive input checking, free-form input, internal plot capability, restart, renodalization, and variable output edits.

The S-RELAP5 code evolved from FRA-ANP's ANF-RELAP code, a modified RELAP5/MOD2 version used by FRA-ANP for PWR plant licensing analyses that included the SBLOCA analysis, steam line break analysis, and PWR non-LOCA Updated Final Safety Analysis Report Chapter 15 event analyses. During the modifications to permit realistic analyses, enhancements were made to incorporate the requirements of 10 CFR Part 50, Appendix K SBLOCA analysis. The code structure was also modified to be similar to that of

RELAP5/MOD3. This included incorporation of the RELAP5/MOD3 reactor kinetics, control systems and trip systems models.

Some of the major modifications made to RELAP5/MOD2 and ANF-RELAP to produce the S-RELAP5 code include the following:

1. <u>Multi-Dimensional Capability</u> - Two-dimensional treatment has been added to the hydrodynamic field equations. This capability can handle the Cartesian and cylindrical coordinate systems.

2. <u>Energy Equations</u> - The energy equations were modified to conserve the energy transported into and out of a control volume, thus correcting the tendency of the RELAP5 codes to produce an energy error when a large pressure gradient exists between two adjacent control volumes.

3. <u>Numerical Solution of Hydrodynamic Field Equations</u> - Where the RELAP5 codes use a Gaussian elimination solver to reduce the hydrodynamic finite-difference equations to a pressure equation, S-RELAP5 uses algebraic manipulation.

4. <u>State of Steam-Noncondensable Mixture</u> - At very low steam quality, the ideal gas equation is used for both steam and noncondensable gas. This permits calculation of state relations for both steam and noncondensable gas at low steam quality and also the presence of pure noncondensable gas below the ice point.

5. <u>Hydrodynamic Constitutive Models</u> - Significant modifications were made to the RELAP5 interphase friction and interphase mass transfer models. Some of the flow regime (two-phase flow) transient criteria were modified to be consistent with published data. Transient flow regimes are introduced for smoothing the constituent models. Most of the RELAP5/MOD2 partition functions were only slightly modified if at all. A more accurate wall friction factor approximation replaces the Colebrook equation.

6. <u>Heat Transfer Model</u> - The RELAP5/MOD2 use of different heat transfer correlations in reflood was eliminated. The Dittus-Boelter single phase steam heat transfer correlation was replaced with the Sleicher-Rouse correlation which gives higher steam temperatures and has a smaller uncertainty range.

7. <u>Choked Flow</u> - The Moody critical flow model was implemented for 10 CFR Part 50, Appendix K calculations. The modification of ANF-RELAP to use an iterative scheme to compute the equation of state at the choked plane rather than using the previous time step information was also implemented.

8. <u>Counter-Current Flow Limit</u> - The Kutateladze type CCFL correlation of ANF-RELAP was replaced with the Bankoff form. This conforms with RELAP5/MOD3.

9. <u>Component Models</u> - The pump model includes the EPRI pump performance degradation data, and the pump head term in the fluid field equations was made more implicit. The ICECON containment code was incorporated to run concurrently with

S-RELAP5. User guidelines were implemented to specify a replacement procedure for modeling the accumulator model.

10. Fuel Models - The RODEX2 fuel deformation and conductivity models were incorporated for SBLOCA applications. The flow diversion model of TOODEE2 was implemented to account for the effect of cladding rupture on heat transfer. The Baker-Just metal-water reaction model was implemented as required by 10 CFR Part 50, Appendix K.

11. Code Architecture - Modifications were made to bring the S-RELAP5 code into conformance with the description of the RELAP5/MOD3 code architecture. This includes writing the code in FORTRAN 77 and maintaining a common source for all computer versions.

4.0 EVALUATION OF S-RELAP5

The staff review concentrated on several areas deemed of greatest importance in the code. Code numerics have long been a problem area. Obtaining adequate convergence, acceptable code running speed, and avoiding numerical diffusion and error generation have long plagued the thermal-hydraulic systems codes. The process by which the requirements of 10 CFR Part 50, Appendix K were developed struggled with specification of heat transfer regimes that would be both conservative and yet correctly represent the variations in heat transfer that were expected to occur in a complex depressurization coolant loss accident. Development of advanced computational methodologies has placed an emphasis on realistic representation of the core neutronics. While this is important for analysis of transient events which are strongly influenced by the core power production, the relatively fast-acting LOCA events can be reasonably represented with simple kinetics models.

When all models and correlations have been individually examined and determined to represent test data, the important question becomes how do the models work together in predicting a system with many interacting components. The staff raised concerns in this area during the time of the review of the lessons learned from the Three Mile Island Unit 2 accident. This led to specification of a minimum set of tests that should be used in assessing the capabilities of analysis codes. Today, twenty years later, the industry has many more sets of test data from, in some cases, larger and better instrumented facilities to use in assessing computer code capabilities. Review of new methodologies necessitates being open to suggestions on the part of the industry of application of those newer test facility experimental programs. The staff encourages use of improved data, with the understanding that proper justification must be given to changing from the tried-and-true specifications that have been used in the past.

Following are the staff views on many of the sections of the code documentation that have been examined. At this point, we would note that the documentation reviewed has errors which have been discussed with the FRA-ANP personnel. The staff bases for approval of documentation are that the material must be understandable to a knowledgeable person, and free of known errors. We have found the documentation to be lacking in several areas. FRA-ANP recognizes our concerns and is in the process of upgrading the documentation. FRA-ANP has plans to submit the S-RELAP5 code for further review for application as a Realistic LOCA code. Both publication of the approved versions of S-RELAP5 documentation for 10 CFR Part 50, Appendix K application and Realistic LOCA application has been stated by FRA-ANP to include error correction. The staff has, in the past, accepted publication of corrected documentation that incorporates the safety evaluation since review of use is performed for applications of the code, plus the staff has at its disposal the ability to inspect and audit the use of an approved code for licensing calculations.

4.1 Two-Fluid Field Equations

In the S-RELAP5 code, the two-phase steam-water mixture is modeled as two fluids. In addition, S-RELAP5 includes methods for handling the presence of noncondensable gas and boron. This results in a model that consists of a total of eight field equations - six equations for the two-phase mixture (two phasic continuity equations, two phasic momentum equations, and two phasic energy equations), one continuity equation for the noncondensable gas, and a boron tracking equation. In Reference 2, the six equations for the two-phase mixture are provided as Equations 2.1 - 2.6, the continuity equation for the noncondensable gas is provided as Equation 2.30, and the boron tracking equation is provided as Equation 2.31. All are presented in vector form. The general form of the field equations used in S-RELAP5 is very similar to those used in other system codes (e.g., RELAP5/MOD2, TRAC-PF-1/MOD1, and COBRA/TRAC). The basic assumption used in the development of the equations is that the average of a product of variables is equal to the product of the average variables. The phasic equations are coupled together via the interfacial processes of vapor generation, heat transfer, and friction. Fluid-wall interaction is included by accounting for the wall friction, wall vapor generation, and wall heat transfer correlations.

For phasic continuity, the liquid fraction and void fraction satisfy the requirements that they sum to unity. The continuity equation for each phase (liquid and vapor) states that, for the phase of interest, the total mass generated is the sum of the mass stored and the mass convected. The sum of the two phasic continuity equations satisfies the requirement that there are no mass sources or sinks in the overall mass continuity equation. This requires that the mass generated for one phase be equivalent to the negative of the mass generated (i.e., the mass consumed) for the other phase. Vapor generation is modeled at the liquid-vapor interface and at the wall. Accordingly, the total vapor generated is taken as the sum of the vapor generated at the interface and that generated at the wall.

For phasic momentum, the momentum equations are presented in the expanded form. The expanded equations are derived by substituting the phasic continuity equations into the phasic momentum equations of the non-expanded form. The expanded form is used in EMF-2100(P) because it is more convenient in the development of the numerical scheme than the non-expanded form. The left-hand-side of each momentum equation contains the terms from the total derivative of momentum. These are the local rate of change of momentum and the convective rate of change of momentum. The right-hand-side contains terms to account for pressure gradient, body force, wall friction, momentum change due to interphase mass transfer, interphase shear (or drag), and the effective force due to virtual mass.

The virtual mass term includes a dependence on mixture density. Mixture density is computed as the sum of the liquid and vapor densities each weighted with its respective phase fraction. The virtual mass term in each momentum equation does not include a spacial derivative component. This simplification was implemented in the development of the NRC's RELAP5/MOD2 code. FRA-ANP stated that this change was necessary because inaccuracies that exist in approximating spatial derivatives for the relatively coarse nodalization used in system representations can lead to nonphysical characteristics in the numerical solutions. In addition, FRA-ANP stated that the simplification is adequate because the primary effect of the virtual mass term is on the mixture sound speed which, in RELAP5, is calculated using an integral model in which the sound speed is based on an objective formulation for the added mass term.

As presented in Reference 2, the sum of the virtual mass terms of the two phasic momentum equations is zero. It is also assumed that the interphase momentum transfer due to friction and due to mass transfer independently sum to zero. This ensures that interphase momentum is conserved. For the terms associated with interphase mass transfer, it is further assumed that the velocity of the fluid at the interface is that of the liquid when the generation of vapor is positive (i.e., for vaporization) and that of the vapor when the generation of vapor is negative (i.e., for condensation).

RELAP5/MOD2's formulation of the phasic energy equations results in errors when the pressure gradient between two adjoining volumes is very large. This is due to neglecting the mechanical energy terms in the formulation of the energy equations for the RELAP5 code. In order to eliminate these errors, the S-RELAP5 phasic energy equations are expressed in the total energy form. By doing this, FRA-ANP retains the mechanical energy terms in their formulation of the phasic energy equations. Simplifying assumptions, however, exclude the local rate of change of energy, wall friction dissipation energy, and potential energy. FRA-ANP justifies this simplification by pointing out that these components of energy are much smaller than the kinetic energy and, therefore, their exclusion does not significantly affect the results.

Phase change at the interface is modeled as a process in which bulk fluid is heated or cooled to the saturation temperature prior to the occurrence of the phase change. This requires that sensible energy exchange be sufficient to bring the fluid to the saturation state. In this model, the wall heat flux is divided into two parts: one part for sensible heat transfer and another part for vapor generation. The vapor generation component is further divided into a fraction that causes vapor generation and a fraction that is used to bring the bulk liquid up to the saturation temperature based on an equal volume exchange. In this model, phasic enthalpies associated with the interphase mass transfer are defined in a manner that satisfies the jump conditions at the liquid-vapor interface. This is done by (1) selecting the enthalpies for the liquid and vapor phases as the liquid specific enthalpy for the liquid, and vapor specific enthalpy at saturation for the vapor when vaporization is taking place; and (2) selecting the enthalpies for the liquid and vapor phases as the liquid specific enthalpy at saturation for the liquid and, vapor specific enthalpy for the vapor when condensation is taking place (note that in each case only one term is at saturation). When the two phasic energy equations are summed, a mixture energy equation is produced. The mixture energy equation must meet the criterion that the interface transfer terms vanish. In S-RELAP5, this criterion is satisfied by requiring that the wall heat transfer terms and the bulk exchange terms each sum to zero independently. In addition, S-REALP5 assumes that the heat transfer from the wall to the vapor is zero for vaporization and that the heat transfer from the wall to the liquid is zero for condensation.

A simple comparison of the change to the energy equation was provided. In this comparison, a calculation of the depressurization of a small diameter pipe at high pressure into a large diameter pipe at low pressure was performed. In this calculation, kinetic and potential energies were negligible and for a perfect system, no change in total internal energy is expected to occur. One calculation was performed using ANF-RELAP which uses the RELAP5/MOD2 energy equations while the other was performed with S-RELAP5 which uses the modified energy equations. The error in energy calculated for this simple example by the two codes demonstrates that the error in the S-RELAP5 calculation is within 0.04 percent while that of ANF-RELAP was approximately -2 percent.

A seventh field equation is provided to track a noncondensable gas component. This equation is a mass conservation equation for the noncondensable gas. In S-REALP5, the noncondensable gas is assumed to be in mechanical and thermal equilibrium with the steam. When noncondensable gas is present, the properties of the vapor phase in the six field equations (two each for continuity, momentum, and energy) are taken as mixture properties.

The eighth and final field equation is a mass conservation equation used to track boron concentration. S-RELAP5 uses an Eulerian tracking model for the boron. The following assumptions are used in this model: (1) liquid properties are not altered by the presence of the boron, (2) boron is transported only in and at the velocity of the liquid phase, (3) energy transported by the boron is negligible, and (4) inertia of the boron is negligible.

S-RELAP5 includes two-dimensional (2-D) modeling capability. Because 2-D modeling adds considerably to the complexity of S-RELAP5 input and running time for the analyses, 2-D modeling will only be used for regions and applications where significant multi-dimensional effects are expected. Application specific topical reports for each S-REALP5 application will describe the use of the 2-D modeling for the application. For SBLOCA, 2-D modeling is applied in the core and downcomer regions. For non-LOCA transient, 2-D modeling was determined to be not required.

4.2 Code Numerics

4.2.1 Semi-implicit Numerical Solution Scheme (SINSS)

The semi-implicit numerical solution scheme is formulated by replacing the system of differential equations with a system of finite-difference equations partially implicit in time. Which terms of the various equations are chosen to be evaluated implicitly are identified as the Semi-Implicit numerical scheme unfolds (Reference 2). However, in all cases the implicit terms were formulated to be linear in the dependent variables at new time. The consequence of this is a linear time-advancement matrix that is solved by direct inversion using a sparse matrix routine (Reference 12). A feature of SINSS is that the implicitness is selected in such a way that the equations can be reduced to a single finite-difference equation per fluid control volume and in terms of hydrodynamic pressure. This solution scheme implies that only an NxN system of finite-difference equations must be solved simultaneously at each time step, where N is the number of control volumes used to simulate the fluid system.

The finite-difference equations developed in the SINSS are based on defining a control volume in which the mass and energy are conserved by equating the accumulation of the fluid mass and energy to the rate of fluid flux through the volume boundaries. This approach enables one to define mass and energy volume average properties as well as define velocities at the volume boundaries. Scalar properties, such as pressure and energy, are defined at the volume centers, and vector quantities, such as velocities, are defined at the boundaries.

4.2.2 One-Dimensional and Multidimensional Formulation

FRA-ANP extended the one-dimensional numerics of RELAP5/MOD2 to include a two-dimensional flow solution scheme in S-RELAP5. The geometric complexity of the reactor vessel lends itself well to modeling in one and two dimensions. Specifically, one could envision selected regions, such as the downcomer, to be modeled in a (z,Θ)-type formulation, while the active region of the core is modeled in a (z,r) formulation. The entire vessel is modeled in one or two-dimensional components with a variety of node sizes, depending on the phenomena to be captured in the particular region in question.

4.2.3 One and Two Dimensional Finite-Difference Formulation

In order to descretize the fluid field differential equations provided on page 2-2 of Reference 2, FRA-ANP set up general guidelines to follow. (Section 2.6 of Reference 2). In particular, mass and energy inventories were considered very important parameters in the development of S-RELAP5 for reactor safety calculations, and the numerical semi-implicit scheme implemented in S-RELAP5 was developed to be consistent and conservative in these quantities. To increase computational speed, the implicit scheme is used for the velocity calculation in the mass and energy terms, that is, for those phenomena known to have small time constants. To further increase computational speed, FRA-ANP opted to linearize implicit terms in new time variables. The ultimate result is the elimination of the need to iteratively solve a system of nonlinear equations. Finally, to allow easy degeneration to homogeneous, or single-phase formulations, the momentum equations are expressed as sum and difference equations (equations 2.80 and 2.81 of Reference 2).

Multi-dimensional finite-difference formulation for the mass and energy balances are similar in form to the one-dimensional formulation. Extension to multi-dimensional flow cases is accomplished by adding subscripts to the appropriate parameters as required to maintain accounting in all directions of the flow. For example, if junction subscripts j+1 and j denote flow in one direction, then for two-dimensional flow we have (i, j+1) and (i,j), where i=x, y for two-dimensional flow, and i is summed over all flow directions. In S-RELAP5 the summation is over all directions, since S-RELAP5 one-dimensional flow formulation allows multiple junctions connected to the control volume. Thus, the algorithm of the summations over all the junctions connecting to a volume already exists.

4.2.4 Solutions to the Finite-Difference Equations

The finite-difference equations (equations 2.101 through 2.110 of Reference 2), are solved numerically for the independent variables P, U_g, U_f, X_n, α_g, $\mathbf{v}_g$, and $\mathbf{v}_f$. There are $2N_j$ momentum equations for N_j junctions and $5N_v$ mass and energy equations for N_v (control) volumes. Once the finite-difference equations are obtained, there is no distinction between one-dimensional, two-dimensional or cross-flow junctions.

The momentum equations are solved at old times, consequently, the phasic velocities for the different junctions are not directly coupled. However, with some algebraic manipulations, the sum and difference momentum equations can be solved for the new-time phasic velocities in terms of new-time pressures of connected neighboring volumes L and k. The new-time pressure of control volume L is coupled to the pressure of neighboring volume k through junction connections.

The new-time saturation temperature, phasic temperature and densities in the finite-difference equations of mass and energy balances, are expressed in terms of the independent state variables, P, U_g, U_f, X_n, using first order Taylor series expansion.

A sparse matrix solver (Reference 12), is used to solve the N_v x N_v matrix for ΔP for each volume. Then these ΔPs are substituted into appropriate equations for computing the new time phasic velocities for all junctions. These pressure changes and phasic velocities are used to obtain the phasic energy solutions for all volumes. Appropriate equations are then used to obtain the non-condensable quality and the new-time void fraction for each volume.

FRA-ANP uses a variety of time step size checks to ensure solution convergence or acceptability. These include material Courant limit checks, mass error checks, water property errors, and excessive extrapolation of state properties in the meta-stable regimes. In S-RELAP5, the size of a newly calculated time step can only be the same as, or half of, or double that of the previous time step. For a system with two-dimensional components, each volume of the two-dimensional components is treated twice, once for the x-direction flow and once for the y-directional flow.

Mitigating numerical anomalies are also addressed in S-RELAP5. These are anomalies which are not usually reduced or removed by simply reducing the size of the time step. Typical anomalies are inconsistent donoring, excessive liquid flowing out of a volume, and water packing. Correction schemes to eliminate or reduce the effect of these anomalies are built into the S-RELAP5 formulation, and the user has no option available to turn off these correction schemes.

4.3 Heat Transfer

4.3.1 Background and General Description

The review of this material consisted of establishing inherent inconsistencies, similarities, formulation and computational results (where and when they existed) between S-RELAP5 and RELAP5/MOD2. During the course of the review, RAIs were developed and transmitted to the applicant. Additional follow-up clarification discussions were held (Reference 13), in support of this effort. The staff did not derive any of the equations associated with the formulated heat transfer correlations other than to verify their source(s) and validity of application. Where applicable, validation of pertinent critical heat flux (CHF) correlations and post-CHF correlations with data were reviewed for accuracy of prediction and error assessment.

Chapter 4 of Reference 2 is a description of the physical models, correlations and methods to obtain the wall-to-fluid heat transfer terms (Q_{wf}, Q_{wg} and Γ_w) in the two-fluid field equations of Chapter 2 of Reference 2. Q_{wf} is the wall heat transfer to the fluid phase, Q_{wg} is the wall heat transfer to the vapor phase, and Γ_w is the mass transfer at the wall. The total heat flux, q'', is partitioned into two phasic heat flux components q''_f and q''_g. The mass transfer term is tied to the bulk inter-phase mass transfer terms and is verifiable through void distribution and phasic temperature measurements.

Most of the heat transfer correlations in-coded in S-RELAP5 are inherited from RELAP5/MOD2 without any modifications or with minor modifications. In the RELAP5/MOD2 code manual, the heat transfer equations are written for the heat transfer rates into the hydrodynamic volumes, while the S-RELAP5 heat transfer equations are expressed in terms of the heat flux and the heat transfer coefficient. The boundary conditions for the conduction solution scheme are expressed in terms of heat transfer coefficients and heat fluxes in both RELAP5/MOD2 and S-RELAP5. The selection logic for heat transfer regimes are essentially the same in both codes.

4.3.2 Heat Transfer Coefficients

The heat transfer coefficients for the liquid state and the nucleate boiling state are obtained from known correlations, such as the Dittus-Boelter turbulent convection correlation for the liquid state (References 14 and 15). The temperature at the inception of boiling is computed from Bergles and Rohsenow (Reference 16). The model for the point of vapor generation was developed by Saha and Zuber (Reference 17). The Chen correlation (Reference 18), is used for both subcooled and saturated boiling. Each of these correlations has been subject to extensive peer review and used in thermal-hydraulic analysis and found to give acceptable results. The staff agrees with use of these correlations.

4.3.3 Critical Heat Flux

The CHF defines the boundary between nucleate boiling and transition boiling. The CHF correlations used in S-RELAP5 are the same as those used in RELAP5/MOD2, that is, the Biasi correlation (Reference 19), for high flow rate and the modified Zuber correlation (Reference 20), for low flow rate. The applicability of these correlations to the appropriate regions (mass fluxes) is well documented in Reference 2.

The CHF temperature, T_{CHF}, is the wall temperature at which the wall-to-fluid heat flux is equal to the critical heat flux. T_{CHF} is obtained by equating the nucleate boiling heat flux of equation 4.15 in Reference 2 to the critical heat flux and solving for T_{CHF}. S-RELAP5 utilizes the Newton-Raphson iterative method to obtain a solution for T_{CHF}.

There is a reflood option that is a user option. The reflood model is turned on when the void fraction is above 0.95. In this case a multiplier is applied to the critical heat flux to reduce the CHF to zero at a void fraction of 1. If the reflood option is turned off, the computation of the CHF temperature is done only when the nucleate boiling heat flux exceeds the critical heat flux.

4.3.4 Transition and Film Boiling

In S-RELAP5 the transition boiling region consists of two parts: the boiling heat transfer to liquid, q''_f, and the convective heat transfer to vapor, q''_g. The heat fluxes in this region are determined from the modified form of the Chen transition heat transfer correlation

(Reference 21). For convective heat transfer, the heat transfer coefficient as proposed by Chen was replaced by a general convective relation, consisting of a turbulent convection correlation of Sleicher-Rouse (Reference 22), natural convection and a laminar flow limit. The Dittus-Boelter correlation used in RELAP5/MOD2 was replaced in S-RELAP5 by the Sleicher-Rouse correlation, which has smaller uncertainties associated with its development (Reference 23).

Sleicher and Rouse investigated and compared several heat transfer correlations to measured data. Their motivation for the investigation was that the Dittus-Boelter correlation was intended to be applicable only to fully developed flow having constant fluid properties. As such, the correlation is inaccurate over certain ranges of Reynolds and Prandtl numbers, in particular, the correlation is approximately 10-25 percent high for gases.

The Sleicher-Rouse correlation was compared to data from four studies of gas flow. The data were for fully developed flow with a wide range of Reynolds number, wall-to-bulk temperature difference, and distance from thermal entrance. The average deviation to measured data was reported to be approximately 4.2 percent.

Based on those findings, FRA-ANP decided to replace Dittus-Boelter with Sleicher-Rouse for wall to vapor convection. The vapor heat transfer was assessed by applying the modified code to FLECHT-SEASET test 33056, a steam cooling test. The calculated wall temperatures from using Sleicher-Rouse are compared with measured data at the 72 inch and 78 inch elevations. The calculated temperature, which is from a point between the 72 inch and 78 inch elevations, falls on the measurement at 72 inches. In comparison, the calculation using Dittus-Boelter shows a slight difference in rod temperature at the same elevation. Both comparisons show good agreement with the measured data. While both correlations show little difference in calculated temperature, there is a lower uncertainty associated with the Sleicher-Rouse correlation. The staff accepts this substitution.

The heat flux in the film boiling region consists of three parts: boiling heat transfer to liquid, convection heat transfer to vapor, and wall-to-fluid radiation. Two correlations are used to compute the boiling heat transfer coefficient: the Forslund-Rohsenow correlation (Reference 24), and the modified Bromley correlation (References 25 and 26). The radiation heat transfer from wall-to-fluid (at high wall temperatures), is determined by using a model developed by Sun (Reference 27).

4.3.5 Special Treatments Core-Reflood

S-RELAP5 has a core reflood option that can be activated by the user. When the reflood model is activated, a fine-mesh re-zoning scheme is used to nodalize the core heat structures into two-dimensional (radial and axial) heat conduction zones. This re-zoning is essential to capture the heat transfer profile covering the entire boiling curve as established in the reactor core. As such, the re-zoned axial nodes extend from the bottom to the top of the active fuel, with the finer zones assigned to regions of nucleate boiling, transition and film boiling. However, FRA-ANP pointed out that no re-zoning is performed on the hydraulic volumes, consequently, all the re-zoned regions retain their assigned hydrodynamic conditions which should result in a more accurate prediction in the boiling heat transfer regimes.

4.3.6 Scaling and Applicability of Correlations

As FRA-ANP pointed out, most of the heat transfer correlations discussed in Chapter 4 of Reference 2 can be found in system codes such RELAP5, TRAC-PF1 (Reference 28), and COBRA/TRAC (Reference 29). Examples of scaling dependency and applicability of the correlations formulated in S-RELAP5 are provided in References 30 and 31. Besides the examples of correlation applicabilities listed in the above references, FRA-ANP included additional assessments in Reference 2:

1. Comparison of S-RELAP5 with Bennett heated tube test data (Reference 32), indicated that the Biasi correlation implemented in S-RELAP5, overpredicts the CHF in the mass flux range 1500–3000 kg/m^2-s, but does a reasonable job in the low mass flow region (100–300 kg/m^2-s) and the high mass flow region, above 3000 kg/m^2-s.

2. S-RELAP5 LBLOCA calculations for LOFT experiments (References 31 and 33), as well as Westinghouse 3 and 4 loop data (References 34 and 35), shows that the core heat flux exceeds CHF in the mass flux range of 5-50 kg/m^2-s during blowdown period. In addition, the S-RELAP5 calculated times to CHF were shorter (earlier) than those calculated for the LOFT experiment. This implies that the CHF correlation in S-RELAP5 conservatively predicts (under-predicts) the time of occurrence of boiling transition for low flux transient conditions.

3. Lueng (Reference 36), also reported that for low mass flux (smaller than 200 kg/m -s), transient data is best predicted by the Griffith-Zuber (modified) correlation in (Reference 20), the same correlation implemented in S-RELAP5. Consequently, the staff agrees with FRA-ANP, in that the approach of combining the Biasi and the modified Zuber correlations for CHF computations is applicable for LOCA calculations.

4. FRA-ANP is fully aware of the shortcomings of applying a steady-state correlation to a transient calculation. However, it opted to use the Chen correlation because of its simplicity and the exponential behavior of the heat flux with the square root of the temperature difference between the wall and the saturation. The correlation was assessed and shown to be valid through comparison with the LOFT experiments, (References 31 and 33), CCTF tests (Reference 37), and FLECHT-SEASET tests (Reference 38).

5. FRA-ANP included in Reference 2 an S-RELAP5 calculation of a convective heat transfer coefficient in the vapor phase. Comparison of calculated wall temperatures with data from two Bennett tube tests, (Reference 32), for two different mass fluxes, 379.7 kg/m -s and 3797.4 kg/m -s, shows good agreement at low mass flux and overpredicts (more conservative) at the high mass flux end. The overprediction at high mass flux is attributed to the consequence of only considering the effect of vapor mass flux in the turbulent convective correlation, and neglecting the fluid flow component (References 32 and 39).

6. For the single phase heat transfer correlation, FRA-ANP replaced the Dittus-Boelter correlation with the Sleicher-Rouse correlation (Reference 22), due its smaller range of uncertainties. Two assessment calculations were performed for the FLECHT-SEASET

steam cooling test 33056 (Reference 40), one, the base case with the base code (i.e., using the Sleicher-Rouse correlation), and the other with the Dittus-Boelter correlation. FRA-ANP provided comparison temperature plots in their submittal for staff review. The plots indicate good agreement between the measured data and the calculated predictions of both correlations. The Dittus-Boelter correlation yields a slightly higher wall temperature in comparison to the Sleicher-Rouse correlations. This is attributed to lower heat transfer to the steam, resulting in lower steam temperature. In addition, FRA-ANP pointed out that an assessment of FLECHT-SEASET forced reflood tests, indicates that the correlation of Sleicher-Rouse yields better calculated-versus-measured data comparison results for the steam temperature.

In general, it appears to the staff that the S-RELAP5 heat transfer modeling schemes and principles are well supported and acceptable.

4.4 The Point Reactor Kinetics Model

The point kinetics model in S-RELAP5 is the same as that used in all the versions of RELAP5. The point kinetics model is used to compute the power in a reactor. The power is computed using the space-independent or point kinetics approximation which assumes that the power can be separated into space and time functions. This approximation is generally accepted for most cases where it is assumed that the space distribution remains constant. The development of the point kinetics equations and their solutions are well documented and referenced in Reference 2.

The kinetics model in S-RELAP5, as with that in RELAP5/MOD2 and MOD3.2, computes both the immediate fission power and the decay power of fission fragments. The user can select the decay power model based on either the American Nuclear Society Proposed Standard ANS 5.1, Decay Energy Release Rates Following Shutdown of Uranium-Fueled Thermal Reactors, revised October 1973 (Reference 41), or the American National Standard for Decay Heat Power in Light Water Reactors, ANSI/ANS-5.1-1979 (Reference 42).

The staff notes that selection of the delayed neutron fraction, β, for the kinetics calculation must be justified as conservative for the core in the as-used state. This is typically done as part of the neutronics analysis of the core. The default value is intended to be used with initial cores.

4.5 Assessment

The staff has stated its position relative to SBLOCA analysis methods in NUREG-0737 (Reference 43), Section II.K.3.30, as:

> *The analysis methods used by nuclear steam supply system (NSSS) vendors and/or fuel suppliers for small-break loss-of-coolant accident (LOCA) analysis for compliance with Appendix K to 10 CFR Part 50 should be revised, documented, and submitted for NRC approval. The revision should account for comparisons with experimental data, including data from the LOFT Test and Semiscale Test facilities.*

The NUREG report goes on to suggest specific tests that might be used to satisfy the above requirement as Semiscale Test S-07-10B and LOFT Test L3-1. Further, the report states that other qualified tests from the entire Semiscale small-break test series and LOFT test series, along with appropriate separate effects tests can be factored into this assessment requirement.

Benchmark calculations were performed by FRA-ANP to fulfill the requirements of NUREG-0737, Section II.K.3.30 utilizing test data from 2-D Flow Tests (References 44 and 45), Semiscale Test S-UT-8 (Reference 46), LOFT Test LP-SB-3 (References 47 and 48), UPTF TEST A5RUN11E (References 49, 50 and 51), and BETHSY Test 9.1b (Reference 52). While none of these are the suggested tests, they are for the most part more current tests and satisfy the intent of the NUREG-0737 suggestions. The staff supports applicants use of newer and better test data to satisfy stated goals.

To demonstrate the adequacy of the S-RELAP5 code for performing SBLOCA analyses, FRA-ANP benchmarked the code and component models against test data. The tests used included two dimensional bundle tests with flow blockage, the Semiscale S-UT-8 test, the boil-off portion of the LOFT LP-SB-03 test, a loop seal clearing test performed in the Upper Plenum Test Facility (UPTF), and the BETHSY 9.1b small break test. Comparisons of the S-RELAP5 calculations to these tests demonstrated, respectively, the capability of S-RELAP5 to conservatively predict 2-D flow phenomena; high pressure, low velocity heat transfer and reflux condensation; loop seal clearing; and overall SBLOCA behavior and temperature results.

The 2-D Flow Tests are a series of separate effects flow blockage tests using test assemblies prototypic of 14x14 Westinghouse assemblies. The data used for the benchmark of S-RELAP5 were previously used to benchmark XCOBRA-IIIC, VIPRE, and THINK-IV for both core flow redistribution and flow redistribution within a single fuel assemble. Three test cases were used for the S-RELAP5 assessment. For the first test, the inlet flow for Assembly A was nominally 1138 gpm while the inlet flow for Assembly B was 512 gpm. For the second test, the inlet flow for Assembly A was nominally 1281 gpm while the inlet for Assembly B was blocked. For the third test, the inlet flow for Assembly A was nominally 1500 gpm while the inlet and outlet for Assembly B were blocked. Comparisons of S-RELAP5 calculations to the data for the first test showed good agreement. Comparisons of the S-RELAP5 calculations to the data for the second test also showed good agreement for axial velocities. However, the comparisons of mass flow fraction at Levels 4 through 7 in Assembly A were not as good as those for the first test. FRA-ANP reported that the velocity measurements at these levels did not conserve total mass flow. Thus it is difficult to draw a conclusion regarding the ability of S-RELAP5 to predict the mass flows for this test. For the third test, S-RELAP5 calculations again compare well to the data. This gives the overall impression that the S-RELAP5 2-D modeling is performing reasonably well.

In addition, FRA-ANP compared the S-RELAP5 calculations for these tests to calculations using XCOBRA-IIIC and THINC-IV, both of which are approved by the NRC for core flow and subchannel analysis of PWR cores. FRA-ANP demonstrated that S-RELAP5 is as good as or better than either of these codes in predicting the test results.

The Semiscale Test S-UT-8 is a scaled PWR integral test designed to investigate the effects of ECCS on SBLOCA, and more specifically, core heat-up before loop seal clearing. The results of the comparisons demonstrated that S-RELAP5 can simulate the core heat-up before loop seal clearing and that the PCTs predicted by S-RELAP5 are conservative but close to the data.

The LOFT Test LP-SB-3 is a scaled PWR integral test designed to investigate core heat transfer during slow boil-off SBLOCA. Differences in comparisons of the ANF-RELAP calculations and the S-RELAP5 calculations were noticed. However, the differences were determined to be insignificant in predicting the LOFT LP-SB-3 test. In addition, comparisons to the data demonstrated that S-RELAP5 is capable of conservatively calculating the boil-off and the fuel heat-up during a SBLOCA.

The UPTF Test A5RUN11E is a full scale PWR separate effect test designed to investigate loop seal clearing behavior with vapor superheat. Comparisons of the S-RELAP calculations to the test showed that S-RELAP5 will overpredict the amount of liquid that remains in the loop seal following the clearing period. S-RELAP5 also overpredicts the pressure drop in the loop seal following clearing. This results in a higher prediction of PCT and is therefore conservative.

The BETHSY Test 9.1b is a scaled PWR integral test designed to investigate SBLOCA behavior without High Head Safety Injection. The test simulates many of the major phenomena in SBLOCA accidents at PWRs. S-RELAP5 calculations were performed to demonstrate the code's capability to predict important SBLOCA phenomena; including, primary and secondary system pressures, core collapsed level, integrated break flow mass, loop seal clearing, and ECCS injection. The comparisons demonstrated that S-RELAP5 can reasonable predict SBLOCA behavior relative to these phenomena. S-RELAP5 closely predicted the loop seal clearing process and the post-clearing behavior. In addition, S-RELAP5 predicted the PCT as 1403°F which was conservative when compared to the measured temperature of 1331°F. The PCT was predicted to occur at essentially the same time as the data.

Numerous additional assessment cases were performed in support of this approval request. Tests such as THTF level swell, Bennett heated tube, CCTF, LOFT large break tests L2-5 and L2-6, and half a dozen additional UPTF tests were used to assess such parameters as rewet/quenching, mixture level, steam generator effects, cold leg stratification, and downcomer modeling. The staff notes that this represents a well thought out approach to code assessment that, while not required for a 10 CFR Part 50, Appendix K methodology, provides the support obtained through a Phenomena Importance and Ranking Table level evaluation.

The staff finds the substitution of test assessments using tests with better supported data acceptable for this application.

5.0 SENSITIVITY STUDIES

One of the requirements for a LOCA analysis is that sensitivity studies must be performed to determine the effects of various modeling assumptions on the calculated peak cladding temperature, PCT. Since S-RELAP5 is intended for application to numerous reactors of two vendors' designs, FRA-ANP chose the three-loop Westinghouse 2300 MWt design for use in performing the S-RELAP5 sensitivity studies.

The break spectrum analysis of the plant found that the limiting small-break is the 2-inch break. Studies were then performed varying the time step size, restart, loop seal model, pump model, radial flow form loss coefficients, and nodalization. In all cases it was found that the effect of each factor studied had an effect on PCT of 5°F or less. Thus, it is concluded that the solution is converged with respect to time step size. In addition, there is very little sensitivity to the various parameters varied during the sensitivity studies.

6.0 CONCLUSIONS

FRA-ANP has modified the approved ANF-RELAP code to produce a code, S-RELAP5, which incorporates the RELAP5/MOD2 code, features of the RELAP5/MOD3 code, the RODEX2 code, the TOODEE2 code, and the ICECON code. The S-RELAP5 code is capable of performing an integrated calculation of a small break loss-of-coolant accident in a PWR of the Westinghouse or Combustion Engineering design.

The code has carried over many of the models of the integrated codes, while improving the numerics of the integrated code. The staff finds this work acceptable.

The FRA-ANP has clarified the applicability of the Sleicher-Rouse heat transfer correlation in place of the Dittus-Boelter correlation. The staff agrees that the Sleicher-Rouse correlation has less uncertainty, and, although it gives a few degrees lower wall temperature for selected experiments, the temperature prediction is more accurate and the use of Sleicher-Rouse is acceptable.

The staff supports the efforts of applicants to integrate codes for analysis of accidents and transients rather than manual transfer of information between the codes. Integrating the thermal-hydraulic, fuel rod performance and containment codes permits a smoother and more accurate prediction of the performance of the system under accident conditions.

The staff reviewed the point kinetics equation model in S-RELAP5 for deviations and/or modifications from the point kinetics model found in the RELAP5 series of codes, and determined that the point kinetics model are identical in both S-RELAP5 and RELAP5/MOD2 and MOD 3.2. Consequently, the point kinetics model in-coded in S-RELAP5 is adequate for its intended use.

The staff notes that a condition imposed on the use of the ANF-RELAP code, (Reference 53), still applies to the use of S-RELAP5. Specifically:

- That while it has been shown in Reference 53 that the thermal-hydraulic phenomena observed for breaks up to 10 percent of the cold leg flow area are the same, if the code is used for break sizes larger than 10 percent of the cold leg flow area additional assessments must be performed to ensure that the code is predicting the important phenomena which may occur.

7.0 REFERENCES

1. EMF-2328(P), Rev. 0, "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based," Siemens Power Corporation, January 2000.

2. EMF-2100(P), Rev. 2, "S-RELAP5 Models and Correlations Code Manual," Siemens Power Corporation, January 2000.

3. XN-NF-82-49(P)(A), Rev. 1, "Exxon Nuclear Company Evaluation Model Revised EXEM-PWR Small Break Model, Supplement 1," Siemens Power Corporation, December 1994.

4. XN-NF-82-49(P)(A), Revision 1, "Exxon Nuclear Company Evaluation Model - EXEM PWR Small Break Model," Exxon Nuclear Company, Inc., June 1986.

5. Ransom, V. H. et al., "RELAP5/MOD2 Code Manual," NUREG/CR-4312, EGG-2396, Rev. 1, March 1987.

6. XN-NF-81-58(P)(A), Revision 2 and Supplements 1 & 2, "RODEX2 Fuel Thermal-Mechanical Response Evaluation Model," Siemens Power Corporation, March 1984.

7. XN-CC-39(A), Rev. 1, "ICECON: A Computer Program Used to Calculate Containment Back Pressure for LOCA Analysis Including Ice Condenser Plants," Exxon Nuclear Company, October 1978.

8. EMF-CC-072(P), Revision 1, "TOODEE2 Code: Model and Input/Output Description," Siemens Power Corporation, March 1997.

9. Ransom, V. H. et al., "RELAP5/MOD3 Code Manual," NUREG/CR-5535, INEL-95/0174, August 1995.

10. Letter, FRA-ANP to NRC, dated January 10, 2000.

11. Request for Additional Information dated December 3, 2000.

12. A.R. Curtis and J.K. Reid, FORTRAN Subroutines for solutions of Sparse Sets of Linear Equations, AERE-R6844,1971.

13. Telecon between FRA-ANP and NRC held on January 4, 2001.

14. F. W. Dittus and L. M. K. Boelter, "Heat Transfer in Automobile Radiators of the Tubular Type," Publications in Engineering, 2, pp. 443-461, University of California, Berkeley, 1930.

15. W. H. McAdams, Heat Transmission, 3rd edition, McGraw-Hill, New York, 1954.

16. A. E. Bergles and W. M. Rohsenow, "The Determination of Forced-Convection Surface-Boiling Heat Transfer," Journal of Heat Transfer, Transactions of ASME, 86, p. 365, 1964.

17. P. Saha and N. Zuber, "Point of Net Vapor Generation and Vapor Void Fraction in Subcooled Boiling," Proceedings of 5th International Heat Transfer Conference, Vol. IV, pp.175-179, 1974.

18. J. C. Chen, "A Correlation for Boiling Heat Transfer to Saturated Fluids in Convective Flow," Process Design and Development, 5, pp. 322-327, 1966.

19. Biasi et. al., "Studies on Burnout Part 3 - A New Correlation for Round Ducts and Uniform Heating and Its Comparison with World Data," Energia Nucleare, 14, pp. 530-536, 1967.

20. P. Griffith, J. F. Pearson, and R. J. Lepkowski, "Critical Heat Flux During a Loss-of Coolant Accident," Nuclear Safety 18, pp. 298-309, 1977.

21. J. C. Chen, R. K. Sundaram, F. T. Ozkaynak, A Phenomenological Correlation for Post-CHF Heat Transfer, NUREG-0237, June 1977.

22. C. A. Sleicher and M. W. Rouse, "A Convenient Correlation for Heat Transfer to Constant and Variable Property Fluids in Turbulent Pipe Flow," International Journal of Heat Mass Transfer, 18, pp. 677-683, 1975.

23. M. J. Thurgood, Recommendation for Determining the Uncertainty in the Peak Clad Temperature Calculated by RELAP5-MOD2/ANF for a Loss-of-Coolant Accident, Numerical Applications Report.

24. R. P. Forslund and W. M. Rohsenow, "Dispersed Flow Film Boiling," Journal of Heat Transfer 90 (6), pp. 399-407, 1968.

25. L. A. Bromley, "Heat Transfer in Stable Film Boiling," Chemical Engineering Progress 46, pp. 221-227, 1950.

26. P. J. Berenson, "Film Boiling Heat Transfer from a Horizontal Surface," Journal of Heat Transfer, pp. 351-358, 1961.

27. K. H. Sun, J. M. Gonzales-Santalo, and C. L. Tien, "Calculations of Combined Radiation and Convection Heat Transfer in Rod Bundles Under Emergency Cooling Conditions."

28. D. R. Liles et al., "TRAC-PF1/MOD1 Correlations and Models," NUREG/CR-5069, LA-11208-MS, December 1988.

29. M. J. Thurgood et al., "COBRA/TRAC-A Thermal-Hydraulics Code for Transient Analysis of Nuclear Reactor Vessels and Primary Coolant Systems," Vol. 1, Equations and Constitutive Models, NUREG/CR-3046 PNL-4385, March 1983.

30. R. A. Dimenna et al., RELAP5/MOD2 Models and Correlations," NUREG/CR-5194, EGG-2531, August, 1988.

31. EMF-92-139(P), Volume 3, Supplement 3, "Realistic LOCA ECCS Evaluation Model Assessment for PWR Large Break Analysis Assessment for LOFT Test L2-5," Siemens Power Corporation, June 1993.

32. A. W. Bennett, G. F. Hewitt, H. A. Kearsey and R. K. F. Keeys, "Heat Transfer to Steam-Water Mixtures Flowing in Uniformly Heated Tubes in Which the Critical Heat Flux Has Been Exceeded," UKAEA Research Group Report, AERE-R 5373, October 1967.

33. EMF-92-139(P), Volume 3, Supplement 4, Realistic LOCA ECCS Evaluation Model Assessment for PWR Large Break Analysis Assessment for LOFT Test L2-6," Siemens Power Corporation, June 1993.

34. EMF-92-139(P), Volume 3, Supplement 6, Realistic LOCA ECCS Evaluation Model Assessment for PWR Large Break Analysis Westinghouse 3-Loop PWR Sample Problem," Siemens Power Corporation, May 1993.

35. EMF-92-139(P), Volume 3, Supplement 7, "Realistic LOCA ECCS Evaluation Model Assessment for PWR Large Break Analysis Westinghouse 4-Loop PWR Example Problem," Siemens Power Corporation, June 1993.

36. J. C. M. Leung, "Transient Critical Heat Flux and Blowdown Heat Transfer Studies," Ph.D. Dissertation, Northwestern University, June 1980.

37. EMF-92-139(P), Volume 3, Supplement 2, "Realistic LOCA ECCS Evaluation Model Assessment for PWR Large Break Analysis Assessment for CCTF Test 54, Siemens Power Corporation," April 1993.

38. EMF-92-139(P), Volume 3, Supplement 1, "Realistic LOCA ECCS Evaluation Model Assessment for PWR Large Break Analysis Assessment for FLECHT SEASET Test 31504," Siemens Power Corporation, April 1993.

39. M. S. Dougall and W. M. Rohsenow, "Film Boiling on the Inside of Vertical Tubes with Upward Flow of a Fluid at Low Qualities, MIT-ME 9079-26, 1963." Journal of Heat Transfer, pp. 414-420, 1976.

40. FLECHT SEASET Program, PWR FLECHT SEASET Unblocked Bundle, Forced and Gravity Reflood Task Data Report, Volume 2, NUREG/CR-1532, EPRI NP-1459, WCAP-9699, June 1980.

41. American Nuclear Society proposed standard, ANS 5.1, "Decay Energy Release Rate Following Shutdown of Uranium-Fueled Thermal Reactors," October 1971, Revised October 1973.

42. American National Standard for Decay Heat Power in Light Water Reactors, ANSI/ANS-5.1-1979, August 1979.

43. NUREG-0737, "Clarification of TMI Action Plan Requirements," U.S. NRC, November 1980.

44. Chelemer, H., P. T. Chu, and L. E. Hochreiter, "THINC-IV - An Improved Program for Thermal-Hydraulic Analysis of Rod Bundle Cores," WCAP-7956, Westinghouse Electric Corporation, June 1973.

45. Weiss, E., R. A. Markley, and A. Battacharyya, "Open Duct Cooling-Concept for the Radial Blanket Region of a Fast Breeder Reactor," Nuclear Engineering and Design, Volume 16, PP 175-386, 1971.

46. "Vessel Coolant Mass Depletion During a Small-Break LOCA," EGG-SEMI-6010, September 1982.

47. "Experimental Analysis and Summary Report on OECD LOFT Experiment LP-SB-3," OECD LOFT-T-3905, December 1985.

48. "Quick Look Report on OECD LOFT Experiment LP-SB-3," OECD LOFT-T-3604, March 1984.

49. "Freiblasen Des Pumpboges Einzeleffekt und Integralversuche, Versuchsdatenbericht," S554/93/007, Siemens AG, Erlangen, Germany, Power Generation Group (KWU), September 1993.

50. "UPTF-TRAM Test Group A Test Results, Analysis," Working Group of Experts Meeting, Mannheim, Germany, Siemens AG, December 6-8, 1993.

51. "UPTF-TRAM Test Instrumentation, Measurement System Identification, Engineering Units and Computed Parameters," S554/92/013, Siemens AG, Erlangen, Germany, Power Generation Group (KWU), November 1992.

52. Clement, P., T. Chataing, and R. Deruaz, "Final Comparison Report for International Standard Problem 27," French original report on BETHSY Test 9.1b.

53. Loomis, G. G., "Summary of the Semiscale Program (1965-1986)," NUREG/CR-4945, July 1987.

SIEMENS

January 10, 2000
NRC:00:002

Document Control Desk
ATTN: Chief, Planning, Program and Management Support Branch
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

Request for Review of EMF-2328(P) Revision 0, "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based"

Fifteen proprietary and 12 nonproprietary copies of topical report EMF-2328(P) Revision 0, "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based," are being submitted to the NRC for review and acceptance for referencing in licensing actions. (NOTE: Three proprietary copies and one nonproprietary copy have been sent directly to Mr. N. Kalyanam.)

The topical report describes a revised SPC Pressurized Water Reactor SBLOCA methodology that incorporates S-RELAP5 as the systems analysis code in place of ANF-RELAP.

The objective in using S-RELAP5 is to apply a single, advanced version of an industry recognized code for all analyses, including LOCA and non-LOCA events. Using a single code that has had extensive review permits the development of one base input deck for the analysis of all events for a particular application. The benefits of using a single code include ease of use by engineers, reduced maintenance requirements, improved quality of both code and applications, and reduction of resources for the NRC review of associated methodology.

It is requested that the NRC approve this report by September 30, 2000, to support plant analyses performed by SPC for its PWR customers.

Siemens Power Corporation considers some of the information contained in the enclosure to this letter to be proprietary. As required by 10 CFR 2.790(b), an affidavit is enclosed to support the withholding of this information from public disclosure.

Very truly yours,

James F. Mallay

James F. Mallay, Director
Regulatory Affairs

Enclosures

cc: R. Caruso
N. Kalyanam (w/Enclosures)
J. S. Wermiel
Project No. 702 (w/Enclosures)

Siemens Power Corporation

2101 Horn Rapids Road
Richland, WA 99352

Tel: (509) 375-8100
Fax: (509) 375-8402

A F F I D A V I T

STATE OF WASHINGTON)
) ss.
COUNTY OF BENTON)

1. My name is Jerald S. Holm. I am Manager, Product Licensing, for Siemens Power Corporation ("SPC"), and as such I am authorized to execute this Affidavit.

2. I am familiar with the criteria applied by SPC to determine whether certain SPC information is proprietary. I am familiar with the policies established by SPC to ensure the proper application of these criteria.

3. I am familiar with the SPC information included in EMF-2328(P) Revision 0, "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based," which is referred to herein as "Document" and is transmitted by letter NRC:00:002. Information contained in this Document has been classified by SPC as proprietary in accordance with the policies established by SPC for the control and protection of proprietary and confidential information.

4. This Document contains information of a proprietary and confidential nature and is of the type customarily held in confidence by SPC and not made available to the public. Based on my experience, I am aware that other companies regard information of the kind contained in this Document as proprietary and confidential.

5. This Document has been made available to the U.S. Nuclear Regulatory Commission in confidence with the request that the information contained in the Document be withheld from public disclosure.

6. The following criteria are customarily applied by SPC to determine whether information should be classified as proprietary:

(a) The information reveals details of SPC's research and development plans and programs or their results.

(b) Use of the information by a competitor would permit the competitor to significantly reduce its expenditures, in time or resources, to design, produce, or market a similar product or service.

(c) The information includes test data or analytical techniques concerning a process, methodology, or component, the application of which results in a competitive advantage for SPC.

(d) The information reveals certain distinguishing aspects of a process, methodology, or component, the exclusive use of which provides a competitive advantage for SPC in product optimization or marketability.

(e) The information is vital to a competitive advantage held by SPC, would be helpful to competitors to SPC, and would likely cause substantial harm to the competitive position of SPC.

7. In accordance with SPC's policies governing the protection and control of information, proprietary information contained in this Document has been made available, on a limited basis, to others outside SPC only as required and under suitable agreement providing for nondisclosure and limited use of the information.

8. SPC policy requires that proprietary information be kept in a secured file or area and distributed on a need-to-know basis.

9. The foregoing statements are true and correct to the best of my knowledge, information, and belief.

Jerold S. Holm

SUBSCRIBED before me this 10th day of January, 2000.

Sue M. Galpin

Sue M. Galpin
NOTARY PUBLIC, STATE OF WASHINGTON
MY COMMISSION EXPIRES: 02/27/00

SUE M. GALPIN
COMMISSION EXPIRES
NOTARY
PUBLIC
FEB. 27, 2000
STATE OF WASHINGTON

SIEMENS

January 18, 2000
NRC:00:006

Document Control Desk
ATTN: Chief, Planning, Program and Management Support Branch
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

Additional Copies of EMF-2328(P) Revision 0, "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based"

Ref.: 1. Letter, J. F. Mallay (SPC) to Document Control Desk (NRC), "Request for Review of EMF-2328(P) Revision 0, 'PWR Small Break LOCA Evaluation Model, S-RELAP5 Based,'" NRC:00:002, January 10, 2000.

The topical report EMF-2328(P) was submitted for NRC review in Reference 1. Three proprietary copies and one nonproprietary copy were provided directly to Mr. N. Kalyanam. SPC subsequently discovered that some of the figures in the report are difficult to read due to poor quality introduced when copying the original report. Three additional copies of this report with improved figure quality are being provided directly to Mr. Kalyanam.

Siemens Power Corporation considers some of the information contained in the enclosure to this letter to be proprietary. The affidavit provided with the original submittal of the referenced topical report satisfies the requirements of 10 CFR 2.790(b) to support the withholding of this information from public disclosure.

If you have any questions or if I can be of further assistance, please call me at (509)375-8757.

Very truly yours,

James F. Mallay, Director
Regulatory Affairs

/arn

Enclosures

cc: N. Kalyanam (w/Enclosures)
Project No. 702

Siemens Power Corporation

2101 Horn Rapids Road
Richland, WA 99352

Tel: (509) 375-8100
Fax: (509) 375-8402

SIEMENS

February 3, 2000
NRC:00:009

Document Control Desk
ATTN: Chief, Planning, Program and Management Support Branch
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

NRC Review of Siemens Power Corporation Topical Reports

Ref.: 1. References are listed on page 2.

Siemens Power Corporation submitted two topical reports for NRC review and approval in References 1 and 2. The methodologies described in the topical reports provided in these two references utilize the code S-RELAP5 to perform transient and safety analyses for PWRs. In support of these two submittals, SPC is providing copies of the S-RELAP5 theory manual (Reference 3), programmer's manual (Reference 4), and user's manual (Reference 5). Eight copies of References 3, 4, and 5 have been provided directly to the NRC project manager for SPC, Mr. N. Kalyanam. SPC is also providing with this letter a CD containing the code S-RELAP5 and specific test cases. The CD also contains codes and files necessary to execute the test cases. The Attachment to this letter provides a description of the contents of the CD and how to extract the information from the CD. The CD has been provided directly to N. Kalyanam.

The version of S-RELAP5 described in References 3, 4, and 5, and contained on the CD, is that used for the analyses presented in the report transmitted by Reference 2 (PWR SBLOCA Methodology). The code version used for the analyses in the report accompanying Reference 1 (PWR Non-LOCA Methodology) was different in one respect. The difference between the two S-RELAP5 versions is in the implementation of the RODEX2 models. Since the RODEX2 model is not utilized for the PWR Non-LOCA methodology, the results are not affected by the difference.

Siemens Power Corporation considers the attachment and the enclosure to this letter to be proprietary. As required by 10 CFR 2.790(b), an affidavit is enclosed to support the withholding of this information from public disclosure.

Very truly yours,

James F. Mallay

James F. Mallay, Director
Regulatory Affairs

Enclosure/Attachment

cc: R. Caruso
N. Kalyanam (w/Enclosures)
R. R. Landry
Project No. 702

Siemens Power Corporation

2101 Horn Rapids Road
Richland, WA 99352
Tel: (509) 375-8100
Fax: (509) 375-8402

Ref.: 1. Letter, J. F. Mallay (SPC) to Document Control Desk (NRC), "Request for Review of EMF-2310(P) Revision 0, *SRP Chapter 15 Non-LOCA Methodology for Pressurized Water Reactors*," NRC:99:048, November 22, 1999.

Ref.: 2. Letter, J. F. Mallay (SPC) to Document Control Desk (NRC), "Request for Review of EMF-2328(P) Revision 0, *PWR Small Break LOCA Evaluation Model, S-RELAP5 Based*," NRC:00:002, January 10, 2000.

Ref.: 3. EMF-2100(P) Revision 2, *S-RELAP5 Models and Correlations Code Manual*, Siemens Power Corporation, January 2000.

Ref.: 4. EMF-2101(P) Revision 1, *S-RELAP5 Programmers Guide*, Siemens Power Corporation, December 1999.

Ref.: 5. EMF-CC-097(P) Revision 4, *S-RELAP5 Input Data Requirements*, Siemens Power Corporation, December 1999.

Contents of CD ROM for S-RELAP5

INTRODUCTION

This 'README' contains instructions for creating an executable version of S-RELAP5, instructions for creating 'xmgr' and 'r2dmx' executables for plotting purposes, and instructions for testing the installation. Also included are descriptions of the contents of the transmittal.

GETTING STARTED

To get started, place the file `'transmittal.Z'` in a suitable subdirectory on the target workstation and uncompress (type in: `uncompress transmittal`). The file 'transmittal' is a 'tar' file, so the next step is to untar the file (type in: `tar –xvf transmittal` at the command prompt). The directory contents should be similar to the following:

```
drwxr-x---  16 t3923      eng          1024 Feb  2 13:50 codes
drwxr-x---   4 t3923      eng            96 Jan 31 16:33 sample_problem
-rw-r-----   1 t3923      eng      33976320 Feb  2 16:40 transmittal
```

BUILDING S-RELAP5

Change directory to `'codes'`. The build script `'build_sr5'` has been tested under both c-shell and korn-shell on both HPUX-9.0 and 11.0 operating systems. If the machine being used operates under the bourne-shell, then switch to c-shell by typing in: `csh`.

Next, type in: `build_sr5`

This command builds S-RELAP5 and executes three sample problems interactively. The output can be redirected to local files by using the following commands:

`build_sr5 >&build_sr5.log &` (for c-shell)
or
`nohup build_sr5 &`
`mv nohup.out build_sr5.log` (for korn-shell)

The executable files will reside in subdirectory `bin`, and the sample problem output will be located in subdirectory `sample`.

BUILDING XMGR

These plotting utilities are included due to incompatibility of S-RELAP5 restart-plot files with the NRC's versions of xmgr and r2dmx. The script creates the plot utilities `xmgr` and `r2dmx` and stores them in the subdirectory `bin`. This script runs under c-shell exclusively. Therefore, to execute `build_xmgr`, type in the following commands:

```
csh
build_xmgr
```

This script is highly dependent on system and local libraries installed on the workstation being used and may abort without creating the necessary executables. If this happens, assistance from the system administrator will be required. An alternative approach would be to try using the `xmgr` and `r2dmx` executable files located in the subdirectory `executables`. The files in this subdirectory will execute on machines using HPUX-9.0 and HPUX-11.0 operating systems.

SAMPLE PROBLEMS

In addition to the check problems used in the build step, a small break LOCA deck and a non-LOCA deck are included with this transmittal. Change directory to `sample_problem` and there are two subdirectories and a script:

```
drwxr-x---   2 t3923      eng           1024 Feb  2 16:34 nonloca
-rwxr-x---   1 t3923      eng            130 Jan 27 10:50 run-sbloca-cases
drwxr-x---   2 t3923      eng           1024 Feb  2 16:37 sbloca
```

The script, which is provided for installation check-out purposes, runs a RODEX2 transient, an S-RELAP5 steady state, and a 100 second S-RELAP5 transient. Both directories contain input files, run scripts, and sample output files. The non-LOCA problem is the turbine trip example from EMF-2310(P), *SRP Chapter 15 Non-LOCA Methodology for Pressurized Water Reactors*. The SBLOCA sample problem is the one presented in EMF-2328(P), *PWR Small Break LOCA Evaluation Model, S-RELAP5 Based*.

Non-LOCA

There are three steady state input decks and one transient deck. The script `runssi` runs the steady state decks and generates a restart file used to start the transient. The `runner` script runs the transient using `trn_in` as the input deck. The '`*.out`' files are provided for checking the installation. There will be small, but insignificant differences between the calculations. These differences are due to compiler differences between operating system versions.

```
-rwxr-x---   1 t3923      eng            360 Jan 27 11:31 runner
-rwxr-x---   1 t3923      eng            605 Jan 27 11:30 runssi
-rw-r-----   1 t3923      eng         638595 Jan 27 11:20 ss_in_1
-rw-r-----   1 t3923      eng           1244 Jan 27 11:21 ss_in_2
-rw-r-----   1 t3923      eng            212 Jan 27 11:21 ss_in_3
-rw-r-----   1 t3923      eng        3349545 Feb  2 15:17 test_ss1.out
-rw-r-----   1 t3923      eng        2844318 Feb  2 15:25 test_ss2.out
-rw-r-----   1 t3923      eng         666004 Feb  2 15:25 test_ss3.out
-rw-r-----   1 t3923      eng        1463598 Feb  2 15:32 test_trn.out
-rw-r-----   1 t3923      eng           7441 Jan 27 11:23 trn_in
```

SBLOCA

The SBLOCA methodology requires a binary file of rod data from RODEX2. This file is made by executing `rdx2lse` (see run script `rdx2.job`), the hp version of RODEX2 that writes the S-RELAP5 readable binary file `rodex2d`. This file must reside in the same directory as the

S-RELAP5 input file for steady state calculations. The `rodex2d` file is not needed for transient calculations.

S-RELAP5 uses the default RELAP5 format for file management; input resides on INPUT, printed output is written to OUTPUT, and the restart-plot file is written to RSTPLT. The script `runssi` shows the job flow for steady state. The script `runner2` shows the job flow for transient calculations. The input used for the transient has an end time of 100 seconds.

The end time for the sample problem is 3500 seconds (see script `runner-3500` and input deck `trn-3500.in`), which takes several hours to execute and is left for the analyst to run overnight.

```
-rw-r-----   1 t3923      eng          137608 Jan 21 16:03 new-base
-rw-r-----   1 t3923      eng           43971 Dec 15 10:33 rdx-eoc
-rwxr-x---   1 t3923      eng              92 Jan 27 10:51 rdx2.job
-rw-r-----   1 t3923      eng           24384 Feb  2 14:33 rodex2d
-rwxr-x---   1 t3923      eng             387 Jan 27 10:53 runner-3500
-rwxr-x---   1 t3923      eng             380 Jan 27 10:52 runner2
-rwxr-x---   1 t3923      eng             361 Jan 27 10:52 runssi
-rw-r-----   1 t3923      eng         1070710 Feb  2 14:33 test-rdx2.out
-rw-r-----   1 t3923      eng         2023398 Feb  2 15:25 test-ssi.out
-rw-r-----   1 t3923      eng          901293 Feb  2 15:46 test-tran.out
-rw-r-----   1 t3923      eng            1140 Jan 21 16:22 trn-3500.in
-rw-r-----   1 t3923      eng            1204 Jan 21 15:34 trn.in
```

EXECUTABLES

The subdirectory `executables`, contains executables made using HPUX-9.0 and are included as back-up in the event that the load steps fail. These files should execute on hp-workstations using HPUX-9.0 and above operating systems. They have been tested on a HPUX-11.0 machine. The files are:

```
-rw-r-----   1 t3923      eng          161872 Feb  2 14:34 STH2XT
-rwxr-x---   1 t3923      eng          107592 Feb  1 09:30 r2dmx
-rwxr-x---   1 t3923      eng          352304 Feb  2 14:34 rdx2lse
-rwxr-x---   1 t3923      eng         1461992 Feb  2 14:34 relap5
-rwxr-x---   1 t3923      eng           28672 Feb  2 14:34 select
-rwxr-x---   1 t3923      eng          385024 Feb  2 14:34 sth2xg
-rwxr-x---   1 t3923      eng         4594340 Feb  1 09:30 xmgr
```

SUB-DIRECTORY DESCRIPTIONS

R2DMX	r2dmx source code
XMGR	xmgr source code
bin	executable files from the build steps
build_sr5	S-RELAP5 build script
build_xmgr	xmgr build script
clean-up	script to remove ‘*.o’ files
envr	source code for the environmental library used by S-RELAP5
eumod1	source code for the eumod1 library used by S-RELAP5

executables	executable files made on a hp-workstation using HPUX-9.0
icecon	source code for the icecon library used by S-RELAP5
libcalls	source code for the SPC library used by S-RELAP5, RODEX2, and environmental library
relap5	source code for S-RELAP5
rodex2	source code for RODEX2
sample	sample problems to test the S-RELAP5 build step
steam	source for water property routines
utils	source for selectx

```
drwxr-x---   2 t3923      eng           1024 Feb  1 09:36 R2DMX
drwxr-x---   5 t3923      eng           6144 Feb  1 09:36 XMGR
drwxr-x---   2 t3923      eng           1024 Feb  2 16:38 bin
-rwxr-x---   1 t3923      eng            651 Feb  2 13:50 build_sr5
-rwxr-x---   1 t3923      eng            292 Jan 27 11:34 build_xmgr
-rwxr-x---   1 t3923      eng            394 Feb  2 16:39 clean-up
drwxr-x---   4 t3923      eng             96 Jan 31 16:30 envr
drwxr-x---   4 t3923      eng             96 Jan 31 16:30 eumod1
drwxr-x---   2 t3923      eng           1024 Feb  1 09:30 executables
drwxr-x---   4 t3923      eng             96 Jan 31 16:30 icecon
drwxr-x---   2 t3923      eng           1024 Feb  2 16:38 lib
drwxr-x---   2 t3923      eng           2048 Feb  2 16:38 libcalls
drwxr-x---   4 t3923      eng             96 Jan 31 16:30 relap5
drwxr-x---   2 t3923      eng           2048 Feb  2 16:38 rodex2
drwxr-x---   2 t3923      eng           1024 Feb  2 14:31 sample
drwxr-x---   4 t3923      eng           1024 Feb  2 14:21 steam
drwxr-x---   2 t3923      eng             96 Feb  2 14:07 utils
```

A F F I D A V I T

STATE OF WASHINGTON)
) ss.
COUNTY OF BENTON)

1. My name is Jerald S. Holm. I am Manager, Product Licensing, for Siemens Power Corporation ("SPC"), and as such I am authorized to execute this Affidavit.

2. I am familiar with the criteria applied by SPC to determine whether certain SPC information is proprietary. I am familiar with the policies established by SPC to ensure the proper application of these criteria.

3. I am familiar with the SPC information transmitted by letter NRC:00:010 and referred to herein as "Document." Information contained in this Document has been classified by SPC as proprietary in accordance with the policies established by SPC for the control and protection of proprietary and confidential information.

4. This Document contains information of a proprietary and confidential nature and is of the type customarily held in confidence by SPC and not made available to the public. Based on my experience, I am aware that other companies regard information of the kind contained in this Document as proprietary and confidential.

5. This Document has been made available to the U.S. Nuclear Regulatory Commission in confidence with the request that the information contained in the Document be withheld from public disclosure.

6. The following criteria are customarily applied by SPC to determine whether information should be classified as proprietary:

(a) The information reveals details of SPC's research and development plans and programs or their results.

(b) Use of the information by a competitor would permit the competitor to significantly reduce its expenditures, in time or resources, to design, produce, or market a similar product or service.

(c) The information includes test data or analytical techniques concerning a process, methodology, or component, the application of which results in a competitive advantage for SPC.

(d) The information reveals certain distinguishing aspects of a process, methodology, or component, the exclusive use of which provides a competitive advantage for SPC in product optimization or marketability.

(e) The information is vital to a competitive advantage held by SPC, would be helpful to competitors to SPC, and would likely cause substantial harm to the competitive position of SPC.

7. In accordance with SPC's policies governing the protection and control of information, proprietary information contained in this Document has been made available, on a limited basis, to others outside SPC only as required and under suitable agreement providing for nondisclosure and limited use of the information.

8. SPC policy requires that proprietary information be kept in a secured file or area and distributed on a need-to-know basis.

9. The foregoing statements are true and correct to the best of my knowledge, information, and belief.

Gerald S. Holm

SUBSCRIBED before me this 3rd day of February, 2000.

AMY R. NIXON
NOTARY PUBLIC
STATE OF WASHINGTON
COMMISSION EXPIRES
DECEMBER 6, 2003

Amy R. Nixon

Amy R. Nixon
NOTARY PUBLIC, STATE OF WASHINGTON
MY COMMISSION EXPIRES: 12/06/03

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

February 11, 2000

Mr. James F. Mallay
Director, Nuclear Affairs
Siemens Power Corporation
2101 Horn Rapids Road
Richland, WA 99352

SUBJECT: REQUEST FOR WITHHOLDING INFORMATION FROM PUBLIC DISCLOSURE - SIEMENS POWER CORPORATION (SPC) TOPICAL REPORT EMF-2328(P), REVISION 0, "PWR SMALL BREAK LOCA EVALUATION MODEL, S-RELAP5 BASED" (TAC NO. MA8022)

Dear Mr. Mallay:

By your letter dated January 10, 2000, and affidavit dated January 10, 2000. executed by Jerald S. Holm, you submitted Topical Report EMF-2328(P), Revision 0, "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based" and requested that it be withheld from public disclosure pursuant to 10 CFR 2.790. A nonproprietary version was submitted for placement in the NRC public document room.

The affidavit stated that the submitted information should be considered exempt from mandatory public disclosure for the following reasons:

"(a) The information reveals details of SPC's research and development plans and programs or their results.

(b) Use of the information by a competitor would permit the competitor to significantly reduce its expenditures, in time or resources, to design, produce, or market a similar product or service.

(c) The information includes test data or analytical techniques concerning a process, methodology, or component, the application of which results in a competitive advantage for SPC.

(d) The information reveals certain distinguishing aspects of a process, methodology, or component, the exclusive use of which provides a competitive advantage for SPC in product optimization or marketability.

(e) The information is vital to a competitive advantage held by SPC, would be helpful to competitors to SPC, and would likely cause substantial harm to the competitive position of SPC."

We have reviewed your application and the material in accordance with the requirements of 10 CFR 2.790 and, on the basis of your statements, have determined that the submitted information sought to be withheld contains proprietary commercial information and should be withheld from public disclosure.

Therefore, the version of the submitted information marked as proprietary will be withheld from public disclosure pursuant to 10 CFR 2.790(b)(5) and Section 103(b) of the Atomic Energy Act of 1954, as amended.

Withholding from public inspection shall not affect the right, if any, of persons properly and directly concerned to inspect the documents. If the need arises, we may send copies of this information to our consultants working in this area. We will, of course, ensure that the consultants have signed the appropriate agreements for handling proprietary information.

If the basis for withholding this information from public inspection should change in the future such that the information could then be made available for public inspection, you should promptly notify the NRC. You also should understand that the NRC may have cause to review this determination in the future, for example, if the scope of a Freedom of Information Act request includes your information. In all review situations, if the NRC makes a determination adverse to the above, you will be notified in advance of any public disclosure.

If you have any questions regarding this matter, I may be reached at 301-415-1480.

Sincerely,

Steph Dembek, FOR

Nageswaran Kalyanam, Project Manager, Section 1
Project Directorate IV & Decommissioning
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Project No. 702

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

April 4, 2000

Mr. James F. Mallay
Director, Nuclear Regulatory Affairs
Siemens Power Corporation
210 Horn Rapids Road
Richland, WA 99352

SUBJECT: ACCEPTANCE REVIEW OF SIEMENS EMF-2310(P), REV. 0, "SRP CHAPTER 15 NON-LOCA METHODOLOGY FOR PRESSURIZED WATER REACTORS," (TAC NO. MA7192) AND EMF-2328(P), REV.0, "PWR SMALL BREAK LOCA EVALUATION MODEL, S-RELAP5 BASED," (TAC NO. MA8022).

Dear Mr. Mallay:

Siemens Power Corporation (SPC), by its letters dated November 11, 1999, and January 10, 2000, submitted topical reports EMF-2310(P), Revision 0, "SRP Chapter 15 Non-LOCA Methodology for Pressurized Water Reactors," and EMF-2328(P), Revision 0, "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based," respectively, and requested review and approval of use of the S-RELAP5 code for application to the PWR small break LOCA and non-LOCA transients. By letter dated February 3, 2000, the supporting documents, listed below, were also submitted to assist the review:

- EMF-2100(P) R2, S-RELAP5 Models and Correlations Code Manual, Siemens Power Corporation, January 2000,
- EMF-2101(P) R1, S-RELAP5 Programmers Guide, Siemens Power Corporation, January 2000,
- EMF-CC-097(P) R4, S-RELAP5 Input Data Requirements, and
- Description of contents of the CD (containing the code S-RELAP5 specific test cases) and how to extract information from the CD.

The S-RELAP5 based thermal-hydraulic analysis code (EMF-2100(P), Revision 2), submitted by Siemens Power Corporation, has been reviewed to determine acceptability of the code documentation for NRC review. The scope and detail of the code documentation pertaining to the thermal-hydraulic modeling, reactor kinetics modeling, code numerics, and code assessment have been reviewed and found sufficient for the staff to initiate its technical review of the application of the code to analysis of the PWR small break LOCA and Chapter 15 non-LOCA transients.

A meeting with the Advisory Committee on Reactor Safeguards (ACRS) Thermal-Hydraulic and Severe Accident Phenomena Subcommittee occurred on March 15, 2000. At that time an overview of the S-RELAP5 code and review schedule was presented. We anticipate providing requests for additional information (RAIs) regarding the technical adequacy of the submittal by early May 2000. We would propose to meet with your staff prior to issuance of any formal RAIs.

If you have any questions regarding the status of the RAIs or the safety evaluation, please do not hesitate to contact Mr. Ralph Landry at (301) 415-1140.

Sincerely,

Stuart A. Richards, Director
Project Directorate IV and Decommissioning
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Project No. 702

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

December 11, 2000

Mr. James F. Mallay
Director, Regulatory Nuclear Affairs
Siemens Power Corporation
2101 Horn Rapids Road
Richland, WA 99352

SUBJECT: REQUEST FOR ADDITIONAL INFORMATION - SIEMENS POWER CORPORATION TOPICAL REPORTS, EMF-2310(P), REVISION 0, "SRP CHAPTER 15 NON-LOCA METHODOLOGY FOR PRESSURIZED WATER REACTORS," (TAC NO. MA7192) AND EMF-2328(P), REVISION 0, "PWR SMALL BREAK LOCA EVALUATION MODEL, S-RELAP5 BASED" (TAC NO. MA8022)

Dear Mr. Mallay:

By letter dated November 22, 1999, Siemens Power Corporation (SPC) submitted Topical Report EMF-2310(P), Revision 0, "SRP Chapter 15 Non-LOCA Methodology for Pressurized Water Reactors," and by letter dated January 10, 2000, Topical Report EMF-2328(P), Revision 0, "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based" for staff review. The primary document describing the S-RELAP5 code is EMF-2100(P), Rev. 2, "S-RELAP5 Models and Correlations Code Manual," dated January 2000. Review of the two topical reports involves reviewing the use of the S-RELAP5 code for application to the small break loss-of-coolant (LOCA) and non-LOCA transients.

In order for the staff to complete its review of the topical reports, the enclosed information pertaining to the S-RELAP5 computer code is required.

A mutually agreeable target date of within 30 days of the date of this letter for your response has been established. If circumstances result in the need to revise the target date, please call me at the earliest opportunity at 301-415-1480.

Sincerely,

N. Kalyanam, Project Manager, Section 1
Project Directorate IV & Decommissioning
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Project No. 702

Enclosure: Request for Additional Information

REQUEST FOR ADDITIONAL INFORMATION

SIEMENS POWER CORPORATION

TOPICAL REPORTS EMF-2310(P), REVISION 0, "SRP CHAPTER 15 NON-LOCA

METHODOLOGY FOR PRESSURIZED WATER REACTORS," AND

EMF-2328(P), REVISION 0, "PWR SMALL BREAK LOCA EVALUATION MODEL,

S-RELAP5 BASED"

PROJECT NO. 702

The following questions are in regard to Topical Report EMF-2100(P), Revision 2.

Comments/Editorials:

G.1 In several places including the first sentence on page 2-1, you stated that the S-RELAP5 code solves two-phase, two-fluid six equations plus one continuity equation for noncondensable gas and a boron tracking equation. S-RELAP5 actually includes a two-fluid model for a two-phase system. The sentence in your report implies that the code models two phases for two different fluids. This is not accurate.

Chapter 1: Introduction

1.1 On page 1-2 you stated that you have applied 2-D modeling to the downcomer, core, and upper plenum. Please explain why 2-D modeling of the lower plenum and lower head has not been applied.

1.2 On page 1-2 you stated that the modification made to the energy equations are more appropriate for analyses involving a containment volume. In Information Notice 92-02 the staff stated that codes in the RELAP5 series are not intended to be used as containment analysis codes. Containment analysis specific codes exist for that purpose. The primary purpose of the RELAP5 codes is analysis of the response of the nuclear steam supply system (NSSS) to accident and transient conditions. Please clarify the intent of your statement in light of the statement in the Information Notice.

1.3 On page 1-6 you stated that the steady-state option does not perform convergence tests and that users are required to set up the conditions for determining whether a steady-state is obtained. Please discuss the guidance provided to the users to aid them in doing this and identify where such guidance has been included.

Chapter 2: Fluid Field Equations and Numerical Solutions

2.1 Please provide a description of the major differences between S-RELAP5 and RELAP5/MOD2 pertaining to the Semi-Implicit Numerical Solution Scheme.

2.2 In the second paragraph on page 2-29, Section 2.6, it is stated that RELAP5/MOD2 was extended to include a two-dimensional flow solution scheme in S-RELAP5. Was this new scheme benchmarked or validated to ensure correct implementation and correctness of the scheme? Please discuss the benchmarking.

2.3 On page 2-54, the subject of time-step control is discussed. How does the time-step calculation in S-RELAP5 differ from that used in RELAP5/MOD2? In particular, discuss any differences in the way the error is measured within the two methods.

2.4 The energy equations presented do not include energy dissipations due to wall friction and pump effects. Please derive your energy equations to show how these terms are eliminated and/or justify the exclusion of these terms. Please justify your simplifying assumption included as Equation 2.13 in your report.

2.5 The energy equations presented assume that the enthalpy in the wall vaporization term ($\Gamma_w h$) is the saturation enthalpy. Please justify this assumption.

2.6 On page 2-6 you stated that under most circumstances, assessment calculations indicate that there are essentially no differences in the results of key loss of coolant accident (LOCA) parameters between the RELAP5/MOD2 energy equations and the energy equations provided in S-RELAP5. Please provide a discussion of the assessment calculations performed including a discussion of the key LOCA parameters that were assessed. In addition, please provide a discussion of the circumstances where differences were identified and justify your methodology in light of those differences. Also, provide similar discussions related to the other transients that you are proposing to analyze with the code.

2.7 Please provide a discussion of the heat transfer at the noncondensable gas-liquid interface and the effect of this on the energy equations. Please explain how this is modeled in your proposed methodology.

2.8 Under Section 2.4, State Relationships, you assume that the interface temperature is the saturation temperature. Please justify this assumption.

2.9 Please derive Equation 2.42 and justify your assumption that the extrapolated κ is just the saturation value for both the superheated liquid and the subcooled steam.

2.10 Your statement that substitution of Equations 2.45 and 2.47 into Equation 2.48 yields Equation 2.50 does not appear correct. Please show how Equation 2.50 was obtained. Note that this error continues in later derivations.

2.11 Regarding Equations 2.101 and 2.102, why is the velocity at j+1 evaluated at time n+1 while being multiplied by the density and void fraction at j+1 from time n? Note that the velocity at j is evaluated at time n and multiplied by the density and void fraction at j from time n. Also, compare with Equations 2.103 through 2.105, wherein the velocity at j+1 is evaluated at time n+1 but multiplied by the density and void fraction at j+1 from time n. But velocity at j is evaluated at time n+1 and multiplied by density and void fraction at j from time n.

2.12 How are areas for the momentum flux terms in the 2-D components calculated? How is this conveyed to the user?

2.13 How are the variables (a_g) and (a_f) in Equation 2.116 defined?

2.14 Given the fact the $r\theta$ is treated as r when using the (z,θ) form of the 2-dimensional momentum equations, as opposed to the (z,r) form, how is the "r" defined?

2.15 Has the effect of violations of the material Courant limit been evaluated? What is the recommended value for $\Delta t_c(i)$ in Equation 2.212?

Chapter 3: Hydrodynamic Constitutive Models

Editorial:

3.1 Page 3-6, first paragraph states that Wallis asserted that $j_{g^*} \approx 0.9$. The star appears incorrectly placed. Consistent with the remainder of the text it appears that the star should be a superscript to j instead of g.

Technical:

3.2 On page 3-1, end of the second paragraph, it is stated that code-data comparisons for the key parameters are to be used for assessing the applicability of the interphase constitutive models. Earlier in the same paragraph it was stated that the key parameters are phasic temperatures, phasic velocities, phasic densities, mass flow rates, and void fractions. Please explain how the key parameters were identified and provide the assessments that were performed to confirm the applicability of the interphase constitutive models.

3.3 [This question is related to large break LOCA (LBLOCA) only and may be responded to at the time of the BE LBLOCA submittal].

On Page 3-1, last paragraph, it is stated that the Electric Power Research Institute (EPRI) drift-flux correlations used in RELAP5/MOD3 are tuned mostly to the steady-state data with regular flow profiles and that there is little evidence that these fix-profile correlations produce good results in simulating LBLOCA transients which are highly irregular and chaotic in nature. It is also stated that the EPRI correlations do not cover the entire range of two-phase flow conditions. Based on this information, it was stated that S-RELAP5 did not adopt the same approach as used in RELAP5/MOD3 but that assessment examples are presented to show that the S-RELAP5 two-fluid formulation produces code-data comparisons that are as good as those obtained by RELAP5/MOD3 for steady-state and nearly steady-state cases. Since the concern stated with the EPRI drift-flux correlations was with the modeling of the LBLOCA transients which are highly irregular and chaotic in nature, please provide the assessments that were performed to ensure that the correlations used in S-RELAP5 are adequate for highly irregular and chaotic transient cases.

3.4 In Equation 3.7, you limited α_L to a minimum value of 0.1 and used $(D^*/19)^8$. Which experiments form the basis for choosing these values? Please justify the use of these values.

3.5 Please describe the tests used in the assessment and provide the assessments performed to validate the use of Equation 3.11 and the limits provided in the text that follows the equation on pages 3-6 and 3-7 in relation to the α_{S-A} criteria.

3.6 On page 3-7, end of the first paragraph, it is stated that introduction of transition regions may reduce the chances of occurrence and magnitude of discontinuities in interphase interaction terms, but it cannot completely eliminate the discontinuities. Please describe known discontinuities that still remain and how these are dealt with in the coding of S-RELAP5.

3.7 Please describe the information used to confirm the validity of the interpolation in Equation 3.15.

3.8 Under the vertical stratification section starting on page 3-8, there appear to be no flow/velocity criteria established for when vertical stratification may occur. Please explain how vertical stratification is detected.

3.9 Please describe how the mixture level model described under the vertical stratification section was validated.

3.10 Please describe the assessment performed to justify the method used for the transition region between the stratified and non-stratified flow (i.e., Equation 3.26 and associated restrictions and criteria).

3.11 Justify the choice of 0.9 for j_g^* for the boundary between slug and annular mist flow (Equation 3.28) in light of the wide range of 0.25 to 1.0 suggested by Wallis. What are the sensitivities of the results of the analyses of interest to the value of j_g^* and why is 0.9 appropriate in light of these sensitivities? What is the range of hydraulic diameters that this criterion is valid for? Please describe the assessment performed to cover the sensitivity to hydraulic diameter. Provide a comparison to applicable experimental data.

3.12 Please describe how the effect of condensation at the ECCS injection point is handled in S-RELAP5.

3.13 Please show how Equation 3.23 is derived from the material in the reference. Also, it appears in Equation 3.23 that the α_g is a subscript to β. Please confirm or correct this.

3.14 On page 3-48, it is stated that various assessment calculations indicate that Equations 3.98 and 3.99 function well. Please identify and discuss the tests that were used in the assessment calculations and the results of the assessment calculations.

3.15 Section 3.4.8 discusses the equilibrium option that exists in S-RELAP5. Please provide a table showing when (i.e., in what transient analyses) this option would be allowed and when it would not be allowed. Also, please provide a reference to the section in the user's manual that directs the user to follow these restrictions. If allowed in any of the licensing analyses, please justify the values selected.

3.16 Section 3.4.9 discusses the effect of noncondensables on condensation rate. Please justify your use of Equations 3.169 and 3.165 in S-RELAP5 to handle the reduction of condensation rate in the presence of noncondensables. Please provide a description and results of assessment calculations that justify the use of these equations.

3.17 For time smoothing, it is stated on page 3-68 that the scheme implemented in S-RELAP5 is empirical and that various assessment calculations indicate that it works satisfactorily. Please describe the assessment calculations performed for confirming the time smoothing scheme. In addition, show how the assessment calculations provide a test for the scheme.

3.18 In Section 3.4.10, in relation to mass error, it is stated that S-RELAP5 implements a strategy which forces only condensation to take place when the amount of liquid in a volume is small and subcooled and the vapor is superheated. In addition, this strategy forces only evaporation to take place when the amount of vapor in a volume is small and subcooled and the liquid is superheated. It is stated that these limits have no significant effects on physical results as one would expect from such a diminishing amount of liquid or vapor and that these limits reduce mass error substantially. Please justify your strategy for dealing with the mass error. In your justification, please discuss any assessments that were performed, the tests used in the assessments, and the results.

3.19 In Section 3.4.10, in relation to subcooled nucleate boiling, it is stated that S-RELAP5 implements a strategy which lowers the interphase heat transfer coefficients in order to eliminate situations where the total mass transfer rate, Γ_g, becomes negative. Please justify your strategy for dealing with this situation. In your justification, please discuss any assessments that were performed, the tests used in the assessments, and the results. In addition, the last paragraph on page 3-70 states that there is no guarantee that the final solution at the end of each time step meets all the conditions or limits described in the section. Please explain what is meant by this statement and explain and justify what is done in S-RELAP5 when the conditions or limits are not met.

3.20 Please provide a list of the figures of merit and important phenomena in relation to each of the transients and accidents to be analyzed with S-RELAP5. Please also describe how these figures of merit and important phenomena were designated as important for the relevant analyses.

3.21 In Sections 3.4.1 through 3.4.7, heat transfer correlations, limits on these correlations, and transition equations are presented for different flow regimes. However, no justifications are provided. Please provide justifications for the material presented in these sections and provide a discussion of assessments performed to confirm the adequacy of correlations used in S-RELAP5.

3.22 Page 3-11, last paragraph, it is stated that "...some calculations with RELAP5/MOD2 indicated that the range of stratified flow is too small. Kukita et al suggested that the vapor velocity on the left side of Equation 3.22 be replaced by the relative velocity (v_g-v_f).

This approach along with an additional constraint to exclude high mass flux conditions was implemented in the previous S-RELAP5 code versions. Recent experience with small break test cases and plant calculations indicated that the new approach might increase code variability. Therefore, the approach of replacing the vapor velocity with relative velocity is abandoned."

Since the approach was abandoned, what was done to address the concern that the range of stratified flow was too small and how was that justified? Please provide comparisons of your approach to data to justify the adequacy of your approach.

3.23 [This question is related to LBLOCA only and may be responded to at the time of the BE LBLOCA submittal].

For dry-wall flow regimes, please justify your use of 0.1 for the α_{IA-IS} criterion in light of the information provided in the text preceeding Equation 3.13 that indicates that the transformation of the three wet-wall flow regimes into inverted annular, inverted slug, and mist flow regimes should be used.

Chapter 4: Heat Transfer Models

4.1 In reviewing Section 4, Heat Transfer Models, it is apparent that this section is totally different to any comparable heat transfer section in RELAP5/MOD2. Contributions from various known sources constitute the basis for this heat transfer model. Please provide qualitative (and quantitative) justification for the formulation of this particular heat transfer model (i.e., assumptions, mass flow rates, pressure, enthalpy, etc.).

4.2 On page 4-2 of the S-RELAP-5 Models and Correlations Code Manual, the last sentence of the last paragraph discusses the issue of reflood being turned off and on. Who decides when or where the option is turned on or off at the appropriate time?

4.3 Please provide an explanation of the difference between the data and the calculational results in Figure 4.3

4.4 How does RELAP-5/MOD2 or MOD3 compare to the same data as that presented in RAI 4.3 above? A comparison of S-RELAP5 and RELAP5/MOD2 against the data and on the same page would help.

Chapter 11: Point Kinetics Model

11.1 On page 11-16, the last equation has a term missing. The term " $-\mathbf{V}_{01}$ " is missing. Compare with Equation 7.6-21 in NUREG/CR-5535, V1.

The following question is in regard to Topical Report EMF-2328(P), Revision 0.

SB.1 Please justify use of 0 percent fuel clad preoxidation in the SBLOCA analysis.

SIEMENS

January 26, 2001
NRC:01:007

Document Control Desk
ATTN: Chief, Planning, Program and Management Support Branch
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

Request for Additional Information – Siemens Power Corporation Topical Reports, EMF-2310(P) Revision 0, (TAC No. MA7192) and EMF-2328(P) Revision 0, (TAC No. MA8022)

Ref.: References are listed on page 2.

In Reference 1, the NRC requested additional information to facilitate the completion of its review of the SPC topical report on the PWR Non-LOCA methodology (Reference 2) and the topical report on the PWR SBLOCA evaluation model (Reference 3). Responses to this request are provided in two attachments: one proprietary and one nonproprietary.

In Reference 4, SPC provided supporting information for the review of these two topical reports. Due to NRC comments regarding typographical errors in the supporting information, SPC is providing revised copies (References 5 and 6). (NOTE: Eight copies of these reports have been provided directly to N. Kalyanam.)

Siemens Power Corporation considers some of the information contained in the attachments and enclosures to this letter to be proprietary. The affidavits provided with the original submittals of the reference reports (References 2, 3, and 4) satisfy the requirements of 10 CFR 2.790(b) to support the withholding of this information from public disclosure.

Very truly yours,

James F. Mallay, Director
Regulatory Affairs

/arn

Attachments - 2/Enclosures – 2

cc: N. Kalyanam (w/Att. & Enc.)
Project No. 702 (w/Att.)

Siemens Power Corporation

2101 Horn Rapids Road
Richland, WA 99352

Tel: (509) 375-8100
Fax: (509) 375-8402

Ref.: 1. Letter, N. Kalyanam (NRC) to J. F. Mallay (SPC), "Request for Additional Information – Siemens Power Corporation Topical Reports, EMF-2310(P), Revision 0, 'SRP Chapter 15 Non-LOCA Methodology for Pressurized Water Reactors,' (TAC NO. MA7192) and EMF-2328(P), Revision 0, 'PWR Small Break LOCA Evaluation Model, S-RELAP5 Based,' (TAC NO. MA8022)," December 11, 2000.

Ref.: 2. Letter, J. F. Mallay (SPC) to Document Control Desk (NRC), "Request for Review of EMF-2310(P) Revision 0, *SRP Chapter 15 Non-LOCA Methodology for Pressurized Water Reactors*," NRC:99:048, November 22, 1999.

Ref.: 3. Letter, J. F. Mallay (SPC) to Document Control Desk (NRC), "Request for Review of EMF-2328(P) Revision 0, *PWR Small Break LOCA Evaluation Model, S-RELAP5 Based*," NRC:00:002, January 10, 2000.

Ref.: 4. Letter, J. F. Mallay (SPC) to Document Control Desk (NRC), "NRC Review of Siemens Power Corporation Topical Reports," NRC:00:009, February 3, 2000.

Ref.: 5. EMF-2100(P) Revision 3, *S-RELAP5 Models and Correlations Code Manual*, Siemens Power Corporation, January 2001.

Ref.: 6. EMF-2101(P) Revision 2, *S-RELAP5 Programmers Guide*, Siemens Power Corporation, January 2001.

S-RELAP5 Request for Additional Information (RAI)

The following are in regard to EMF-2100(P) Rev. 2:

Comments/Editorials:

G.1 *In several places including the first sentence on Page 2-1, you stated that the S-RELAP5 code solves two-phase, two-fluid six equations plus one continuity equation for noncondensable gas and a boron tracking equation. S-RELAP5 actually includes a two-fluid model for a two-phase system. The sentence in your report implies that the code models two phases for two different fluids. This is not accurate.*

The S-RELAP code solves two-fluid six equations plus one continuity equation of noncondensable gas and a boron tracking equation for flow of a two-phase steam-water mixture which can contain a noncondensable in the vapor phase and a soluble in the liquid phase.

Chapter 1: Introduction

1.1 *On Page 1-2 you stated that you have applied 2-D modeling to the downcomer, core, and upper plenum. Please explain why 2-D modeling of the lower plenum and lower head has not been applied.*

The S-RELAP5 2-D component is flexible and can be applied to any selected component through input, and the 2-D modeling has been successfully applied to various RCS components, including the lower head and plenum. Use of the 2-D model adds considerably to the complexity of the system input and running time of the analysis model. Therefore, SPC methodologies will invoke the use of the 2-D model only for regions in applications where significant multi-dimensional effects are expected. Thus, the use of the S-RELAP5 2-D model will be different depending on the licensing application.

For SBLOCA applications, 2-D modeling is applied in the core and downcomer regions. Significant multi-dimensional effects which would require 2-D modeling in the lower plenum and lower head are not expected for SBLOCA. For non-LOCA transients, the 2-D capabilities are not required. The methodology topical reports for each S-RELAP5 application describe the use of the 2-D modeling for that specific application.

1.2 *On Page 1-2 you stated that the modification made to the energy equations are more appropriate for analyses involving a containment volume. In Information Notice 92-02 the staff stated that codes in the RELAP5 series are not intended to be used as containment analysis codes. Containment analysis specific codes exist for that purpose. The primary purpose of the RELAP5 codes is analysis of the response of the NSSS to accident and transient conditions. Please clarify the intent of your statement in light of the statement in the Information Notice.*

During a PWR LBLOCA, a coupling exists between reflood heat transfer and containment back pressure. Calculation of this coupling requires that accurate mass and energy release data be provided to the containment code calculation which then feeds back the appropriate back pressure for the reactor system calculation. To correct the problem associated with the Information Notice, changes were made to the S-RELAP5 code to provide energy conservation for all conditions. In addition, changes were made to incorporate the ICECON containment code into S-RELAP5, and to interface the containment code calculation so that the containment calculation is performed as part of S-RELAP5 in parallel with the NSSS transient calculation.

The energy equation changes were made to directly address the problem identified by Northeast Utilities which resulted in Information Notice 92-02. It was found that the base RELAP5 code did not conserve energy when critical flow was calculated with a large pressure drop between volumes such as from the NSSS to the containment during a LBLOCA event. This means that the mass and energy release to the containment calculated by the then existing versions of the RELAP5 code could be erroneous and results from these code versions should not be used as the source terms for containment analysis performed with either RELAP5 or a containment analysis code.

The energy equations in the base RELAP5 code are formulated in terms of thermal energy. With this formulation, P-V work terms are not calculated accurately. For the large pressure drop conditions, this results in an energy conservation error. The S-RELAP5 energy equations are formulated in terms of total energy which conserves energy over all pressure drop conditions.

In the coupled NSSS and containment calculation, the mass and energy release to a time dependent volume is calculated by S-RELAP5 for one time step. This information is then passed to the ICECON (CONTEMPT) portion of S-RELAP5 where the updated containment back pressure is calculated. Back pressure is then passed back to the time dependent volume and applied as a boundary condition on the NSSS calculation for the next time step. Since energy is conserved using the S-RELAP5 code, and this code now contains the ICECON containment module, the containment pressure can be determined using S-RELAP5.

It should be noted that the energy equation changes in the S-RELAP5 documentation have little effect on S-RELAP5 calculations for SBLOCA or non-LOCA transients, and that containment pressure is not calculated for these methodologies. The changes are necessary and important for the planned submittal of the realistic LOCA methodology, and the applications described apply only to that methodology. This change also would be important if mass and energy release are calculated for use in a containment analysis code such as GOTHIC.

1.3 *On Page 1-6 you stated that the steady-state option does not perform convergence tests and that users are required to set up the conditions for determining whether a steady-state is obtained. Please discuss the guidance provided to the users to aid them in doing this and identify where such guidance has been included.*

SPC develops user guidelines for each event analysis and a guideline for input deck generation. Those guidelines include specific requirements for developing steady- state controllers, as well as guidelines for establishing criteria for acceptable steady-state conditions. Currently, those guidelines are specific to using ANF-RELAP for the thermal hydraulic portion of the transient.

Upon acceptance of the proposed methodologies, the guidelines will be updated to reflect the differences between the use of ANF-RELAP and S-RELAP5. However, both the SBLOCA and non-LOCA analyses will use the current ANF-RELAP guidelines for establishing steady-state acceptance criteria.

The criteria for establishing steady-state calculation acceptance for any of the events are as follows:

The calculated results from the null transient using the steady-state option are examined closely to ensure that a true steady-state condition has been established. This is achieved by examining specific parameters (listed below) and comparing them against the desired steady-state plant conditions. Reasonable stability and comparison of these parameters with known steady-state values would indicate an acceptable steady-state condition has been achieved. Current guidelines recommend that plots of the key parameters be included in the calculation notebook, so the attainment of a steady-state can be visually verified.

The following are parameters are recommended for inspection to assure steady conditions have been reached:

- Reactor power
- Primary pressure
- Loop pressure drop
- Loop flow rate
- Core bypass and leakage path flow rates
- Vessel upper head temperature
- Cold leg temperature
- Hot leg temperature
- SG secondary pressure
- SG secondary mass inventory
- SG secondary void profile
- SG feedwater and steam flow rates
- SG recirculation ratio
- Mass flow rates in the SG boiler region
- Pressurizer collapsed liquid level
- Core collapsed liquid level
- Hot channel wall temperatures
- Core mass flow

Chapter 2: Fluid Field Equations and Numerical Solutions

2.1 *Please provide a description of the major differences between S-RELAP5 and RELAP5/MOD2 pertaining to the Semi-Implicit Numerical Solution Scheme.*

[

] The detailed algebraic manipulation is shown in Equations (2.131) to (2.195). The Gaussian solver without pivoting may lose significant accuracy under some circumstances (e.g., when the matrix is nearly singular); therefore, the RELAP5/MOD2 method is not used. Another difference is the more implicit treatment of the pump junction velocities, which is described on Pages 2-40 to 2-41 [Equations (2.118 to (2.124)].

2.2 *In the second paragraph on Page 2-29, Section 2.6, it is stated that RELAP5/MOD2 was extended to include a two-dimensional flow solution scheme in S-RELAP5. Was this new scheme bench-marked or validated to ensure correct implementation and correctness of the scheme? Please discuss the bench-marking.*

The S-RELAP5 two-dimensional flow scheme was verified and validated. Two types of benchmark cases were used to verify/validate the 2-D model: cases with known solutions and comparisons to multi-dimensional flow data. Calculations of cases with known solutions, such as 2-D symmetrical fill problems, validate correct implementation of the 2-D model. Comparisons with measured data show the validity of the model. A symmetric fill problem was set up for the (z,θ)-type 2-D component to check if correct velocities and flow symmetry are calculated in the 2-D model. The 2-D nodalization scheme is similar to that used for modeling the reactor vessel downcomer. The calculation shows that the liquid advances with the same velocity as the injection (time-dependent junction) velocity in all vertical directions and flow symmetry is maintained throughout the entire period, including the period after the 2-D component completely fills. This verifies that the 2-D momentum flux terms are correctly treated. A similar exercise was performed on the (z,x)-type 2-D component, producing correct results. Since the plant steady-state conditions such as flow rates, velocities, and flow patterns are known, the plant steady-state calculations can also be used to check the correctness of the 2-D model implementation.

The purpose of a comparison with test data using the 2-D component is to validate its applicability for modeling multi-dimensional flow problems. Two-dimensional flow test comparisons performed specifically to validate the S-RELAP5 2-D modeling are given in section 5.1 of the SBLOCA topical EMF-2328(P). Section 5.5.2 of EMF-2100(P) also discusses results from a UPTF simulation where the (z,θ)-type 2-D component was used to model a downcomer. The calculated results shown in Figure 5.17 on Page 5-60 of EMF-2100(P) demonstrate that a proper velocity profile was obtained in that simulation.

2.3 *On Page 2-54, the subject of time-step control is discussed. How does the time-step calculation in S-RELAP5 differ from that used in RELAP5/MOD2? In particular, discuss any differences in the way the error is measured within the two methods.*

In S-RELAP5 the time step control is performed through four criteria: (1) material Courant limit {Equation (2.211)}, (2) consistency check on the mass solution {Equation (2.213)}, (3) consistency check on the energy solution {Equation (2.214)}, and (4) Failure of equation of state. For the Courant limit, RELAP5/MOD2 implements a partial violation of the Courant limit. The partial violation scheme is present in the S-RELAP5 code, but is not used, i.e., no partial violation of Courant limit is allowed. RELAP5/MOD2 does not have item (3) and adds a measure of overall system mass differences in item (2). The criteria for the mass consistency check are 1×10^{-3} (repeat) and 1×10^{-4} (double) [see description below Equation (2.213)] in the S-RELAP5 Theory Manual, and are 2×10^{-3} and 2×10^{-4} in RELAP5/MOD2. Both S-RELAP5 and RELAP5/MOD2 check the mass conservation by computing the accumulated mass generation (or destruction) in the system, which is shown on the major edit as mass error. This system mass error is not used in time-step control in S-RELAP5 and the RELAP5 codes.

2.4 *The energy equations presented do not include energy dissipations due to wall friction and pump effects. Please derive your energy equations to show how these terms are eliminated and/or justify the exclusion of these terms. Please justify your simplifying assumption included as Equation 2.13 in your report.*

The energy equations in S-RELAP5 are expressed in the total energy form. The terms in Equations (2.4) and (2.5) plus Equation (2.13) can be identified from the following general statement of the law of conservation of energy for the fluid in a control volume:

$$\left\{\begin{array}{c}\text{rate of}\\ \text{accumulation}\\ \text{of internal}\\ \text{and kinetic}\\ \text{energy}\end{array}\right\} = \left\{\begin{array}{c}\text{rate of}\\ \text{internal and}\\ \text{kinetic energy}\\ \text{in}\\ \text{by convection}\end{array}\right\} - \left\{\begin{array}{c}\text{rate of}\\ \text{internal and}\\ \text{kinetic energy}\\ \text{out}\\ \text{by convection}\end{array}\right\}$$

$$+\left\{\begin{array}{c}\text{net rate of}\\ \text{heat addition}\\ \text{by conduction}\end{array}\right\} - \left\{\begin{array}{c}\text{net rate of work}\\ \text{done by system}\\ \text{on surroundings}\end{array}\right\}$$

(see Page 311 of Transport Phenomena by R. B. Bird, W. E. Stewart, and E. N. Lightfoot, 1960.)

[

]

2.5 *The energy equations presented assume that the enthalpy in the wall vaporization term ('wh) is the saturation enthalpy. Please justify this assumption.*

The product $\left(\Gamma_w\, h_k^s\right)$ represents the energy transfer for phase *k* (either addition or subtraction) associated with the mass transfer due to the "wall vapor generation" term. In subcooled boiling, Γ_w is positive and the energy transferred to the vapor within the control volume is $\left(\Gamma_w\, h_g^s\right)$ as it should be. The implication is that the generated vapor appears at the saturation temperature corresponding to the local pressure. The energy removed from the liquid phase within the control volume is then $\left(\Gamma_w\, h_f^s\right)$. As the liquid phase is subcooled, there appears to be an energy imbalance with the magnitude $\left[\Gamma_w\left(h_f^s - h_l^s\right)\right]$ corresponding to the liquid sensible heat that must be added to bring the subcooled liquid up to the saturation temperature. This energy imbalance does not exist because this sensible heat requirement has already been accounted for through the determination of the fraction of the wall heat flux that causes vapor generation (see Equation (4.27) of Section 4.3.2) as discussed below.

S-RELAP5 uses the Lahey subcooled boiling model. The wall heat flux is first divided into two parts: one for sensible heat transfer and one that is "available" for vapor generation (denoted as q''_{wv} in the manual). This heat flux that is available for vapor generation is then further partitioned into a fraction that actually causes vapor generation $\left(q''_{evap}\right)$ and that corresponding to the sensible heat transfer needed to bring the bulk liquid up to the saturation temperature based on an equal volume exchange $\left(q''_{pump}\right)$. Thus, the sensible heat transfer due to this "pumping" term accounts for the energy transfer needed to bring the mass of subcooled liquid that is being evaporated up to the saturation temperature.

2.6 *On Page 2-6 you stated that under most circumstances, assessment calculations indicate that there are essentially no differences in the results of key loss of coolant accident (LOCA) parameters between the RELAP5/MOD2 energy equations and the energy equations provided in S-RELAP5. Please provide a discussion of the assessment calculations performed including a discussion of the key LOCA parameters that were assessed. In addition, please provide a discussion of the circumstances where differences were identifies and justify your methodology in light of those differences. Also, provide similar discussions related to the other transients that you are proposing to analyze with the code.*

The referenced assessment calculations were from undocumented developmental assessment results using LOFT L2-5, LOFT L2-6, CCTF Run 54, and FLECHT-SEASET Test 31504. Those calculations were made at the time of the energy equation modification. The stated differences were from comparing the previous results without the model changes with results having the model changes implemented. The parameters compared were cladding temperatures, steam temperatures, void fractions and pressures. The model had essentially no effect on the calculated result, as expected, since the system models did not include containment modeling (e.g., a large pressure drop across a choke plane).

The non-LOCA sample problems show comparisons between ANF-RELAP, which uses the same energy equations as RELAP5/MOD2, and S-RELAP5 calculated results. Those comparisons show that S-RELAP5 is essentially equivalent to ANF-RELAP for the modeling of non-LOCA transients Page 2-1, EMF-2310(P).

The SBLOCA methodology does not include containment modeling, therefore there are no expected differences in the results.

The Realistic LBLOCA model simulates the interaction between primary system and the containment response to blowdown. In this situation, the correct energy transfer to the containment model is necessary.

A demonstration calculation can be made to show the energy error when using the S-RELAP5 energy equations compared to the RELAP5/MOD2 energy equations. Consider a closed system where potential and kinetic energies are negligible and consisting of a small diameter pipe (1 m) at high pressure (150 bar) blowing down into a large diameter pipe (10 m) at low pressure (1 bar) through an orifice. Since there is no change in total internal energy in a perfect system, a comparison of initial internal energy to the transient internal energy during the blowdown should indicate net internal energy error.

A calculation of this type was made with both S-RELAP5 and ANF-RELAP (ANF-RELAP uses RELAP5/MOD2 energy equations). The results in Figure 1 show that energy is conserved to within 0.04% by S-RELAP5 while ANF-RELAP shows an error of approximately -2%. These results imply that there will be a much smaller energy error when transferring energy out of a system (i.e., coupled primary and containment calculation) using S-RELAP5 compared to a code using the RELAP5/MOD2 energy equations.

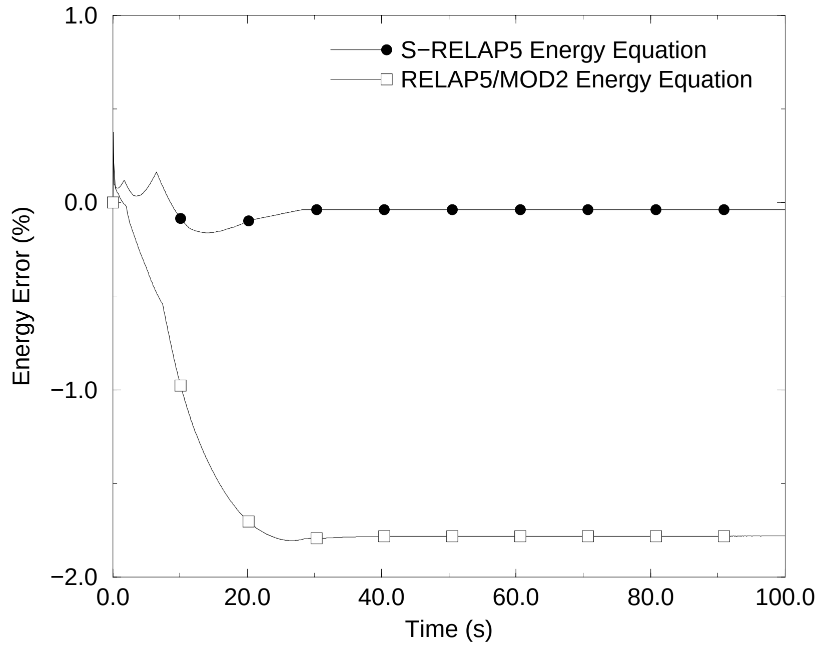


Figure 1. Comparison of energy error between S-RELAP5 and RELAP5/MOD2 energy equations

2.7 *Please provide a discussion of the heat transfer at the noncondensable gas-liquid interface and the effect of this on the energy equations. Please explain how this is modeled in your proposed methodology.*

The noncondensable interphase heat transfer is described in Section 3.4.9 {pp. 3-65 - 3-66 of EMF-2100(P)}. The effect of the model on the energy equations is handled through the interphase heat transfer terms in the energy equations (see Equations (2.5), (2.6) and the discussion on Pages 2-3 to 2-9). For SBLOCA and non-LOCA events, the noncondensable does not leave the accumulators; therefore, the noncondensable interphase heat transfer model has no effect. For LBLOCA, the entering of the noncondensable into the cold legs after the accumulators are emptied of water reduces the steam condensation rate, and thus, increases the cold leg pressures. This in turn causes a surge of ECC water into the core and provides additional cooling for a short period. It has a weak to moderate effect on the clad temperatures during the reflood phase of a LBLOCA.

2.8 *Under Section 2.4, State Relationships, you assume that the interface temperature is the saturation temperature. Please justify this assumption.*

The interface temperature is assumed to be at saturation for the modeling of the interphase heat transfer. The state relationship provides a computation of derivatives at the saturation temperature so that the interphase heat transfer terms can be linearized and treated implicitly.

It is a standard approach to use the saturation temperature as the reference temperature for formulating the interphase heat transfer model. The net effect of the interphase heat transfer model is to compute the amount of mass exchanged between the two phases. That is, the heat transfer from a phase to the saturation interface is just an intermediate step and the significant quantity is the heat transfer between the phases. At the equilibrium state, both phases are saturated. Setting the reference (interface) temperature to saturation provides a convenient measure of the deviation of a phase from equilibrium and simplifies the interphase heat transfer model.

2.9 *Please derive Equation 2.42 and justify your assumption that the extrapolated κ is just the saturation value for both the superheated liquid and the subcooled steam.*

Equation (2.42) has a typographical error. The corrected form, and the derivation is provided in the following text.

Equation (2.42) will be corrected in the next revision of the models and correlations document EMF-2100(P).

2.10 *Your statement that substitution of Equations 2.45 and 2.47 into Equation 2.48 yields Equation 2.50 does not appear correct. Please show how Equation 2.50 was obtained. Note that this error continues in later derivations.*

There is a typographical error in Equation (2.47): the "+" should be "=". That is, Equation (2.47) should be

$$V_g = X_n V_n = (1-X_n) V_v$$

The above equation is a direct consequence of the Gibbs-Dalton assumption that all gases (i.e., steam and noncondensables) occupy the same space. This equation will be corrected in the next revision to the models and correlations document, EMF-2100(P).

2.11 *Regarding Equations 2.101 and 2.102, why is the velocity at j+1 evaluated at time n+1 while being multiplied by the density and void fraction at j+1 from time n? Note that the velocity at j is evaluated at time n and multiplied by the density and void fraction at j from time n. Also, compare with Equations 2.103 through 2.105, wherein the velocity at j+1 is evaluated at time n+1 but multiplied by the density and void fraction at j+1 from time n. But velocity at j is evaluated at time n+1 and multiplied by density and void fraction at j from time n.*

There are typographical errors in Equations (2.101) and (2.102). The velocities at junction j should be superscripted with n+1. These changes will be made to the next revision of EMF-2100(P).

The time level difference between the velocity and mass, energy, or quality parameter is from the assumptions used in developing the semi-implicit numerical scheme. In the discussion in Section 2.6 of EMF-2100 (P), Rev 2., a reference is made to implicit terms formulated to be linear in the dependent variables at new time. The mass, energy, and noncondensable quality fluxes are those terms. Note that the momentum flux terms in Equations (2.109) and (2.110) consist of old time, or time level n, velocities. This allows the momentum equations to be reduced to Equation (2.116), the velocity at time level n+1. These new time velocities can be substituted into Equations (2.101) through (2.105) and yield expressions for mass, energy, and noncondensable quality in terms of ΔP. With appropriate substitutions, those equations can be combined into a single expression in terms of ΔP. The process is discussed in detail starting on Page 2-43.

2.12 *How are areas for the momentum flux terms in the 2-D components calculated? How is this conveyed to the user?*

The areas appear in the 2-D (and 1-D) momentum flux terms only indirectly through the volume average velocities, which are defined in Equations (2.98) - (2.100). The user usually provides the lengths and volumes of the 2-D nodes through input and the code calculates the areas by: area = volume/length. The user may also have to provide the junction areas according to the actual geometry. The S-RELAP5 Input Data Requirements section of the S-RELAP5 users' manual, EMF-CC-097(P), has a section for the 2-D component input prescription. Additional procedures will be discussed in the methodology guidelines.

2.13 *How are the variables (a_g) and (a_f) in Equation 2.116 defined?*

2.14 *Given the fact the $r\theta$ is treated as r when using the (z, θ) form of the 2-dimensional momentum equations, as opposed to the (z,r) form, how is the "r" defined?*

In the cylindrical (z,θ) 2-D system, r is measured from the origin and $r\Delta\theta$ is the length of the arc for the angle $\Delta\theta$. Since r is constant, $r\Delta\theta = \Delta(r\theta)$= arc length of an azimuthal sector. In the (z,r) system, Δr is the nodal length in the r-direction, which is the distance between two radial rings.

2.15 *Has the effect of violations of the material Courant limit been evaluated? What is the recommended value for $\Delta t_c(i)$ in Equation 2.212?*

Violation of the material Courant limit often leads to unstable solutions in the semi-implicit scheme. In the earlier years of RELAP5 development, partial violation of the Courant limit was considered to be acceptable if the solution was stable. However, its effect is difficult to quantify. Therefore, partial violation of the Courant limit is no longer used in S-RELAP5 applications. As stated in the paragraph below Equation (2.212), i=1 is used, i.e., no partial violation of the Courant limit.

Chapter 3: Hydrodynamic Constitutive Models

Editorial:

3.1 *Page 3-6, first paragraph states that Wallis asserted that $j_{g^*} \approx 0.9$. The star appears incorrectly placed. Consistent with the remainder of the text it appears that the star should be a superscript to j instead of g.*

Concur. The typo will be corrected.

Technical:

3.2 *On Page 3-1, end of the second paragraph, it is stated that code-data comparisons for the key parameters are to be used for assessing the applicability of the interphase constitutive models. Earlier in the same paragraph it was stated that the key parameters are phasic temperatures, phasic velocities, phasic densities, mass flow rates, and void fractions. Please explain how the key parameters were identified and provide the assessments that were performed to confirm the applicability of the interphase constitutive models.*

The key parameters were identified from analysis of the interphase constitutive models and their usage in the mass, energy, and momentum conservation equations. The constitutive models have an effect on mass fractions, temperatures, and slip. The parameters characterizing those phenomena are then void fraction, phasic densities, phasic temperatures, and phasic velocities. Flow rate is consequence of those preceding parameters.

Based on past experience and informal peer reviews, an informal PIRT was developed (see response to RAI 3.20). In the PIRT, processes and phenomena were ranked as having high importance, medium importance, and low importance during the five periods of a SBLOCA transient. Those processes which were ranked as having high importance established a basis for which of the S-RELAP5 models received rigorous assessment and the experimental data sets that were used for the assessment. Additionally, periods of two-phase flow could be identified in the PIRT. The experiments identified in the PIRT included the S-RELAP5 standard test set (STS), four SBLOCA specific tests, and a 2-Dimensional flow test. The STS consists of a wide range of experiments that are used to validate code performance and are exercised for each code version created for production use. The additional SBLOCA specific experiments are used primarily as phenomenological assessments in addition to model assessments. The 2-Dimensional test was used to validate the S-RELAP5 2-Dimentional capability.

The interphase constitutive models, interphase drag and interphase mass transfer, were assessed in the context of best possible performance under all conditions, as well as specific to SBLOCA transients.

In EMF-2100(P), results from several of the tests that make up the STS are presented. Listed below are those experiments with brief descriptions of the key parameters with references to their location in EMF-2100(P):

- <u>GE Level Swell</u> – The test assesses the level model, interphase friction, and interphase mass transfer. Key parameters are void fraction and liquid level. Discussion of results begins on Page 3-42 and void profiles are shown in Figures 3.5 and 3.6 on Page 3-43.

- <u>THTF Tests 3.09.10j, 3.09.10m, and 3.09.10dd</u> – The tests are steady boiling tests with level swell and are representative of the core boiling process during SBLOCA. They are used specifically for interphase friction and subcooled boiling assessments. The key parameter is void fraction. The discussion of results begins at the bottom of Page 3-43 and void profiles are shown in Figures 3.7 through 3.9 on Pages 3-44 through 3-45.

- <u>Bennett Heated Tube Tests 5358 & 5379</u> – Tests used to validate transient CHF. These are not applicable to SBLOCA. The key parameter is wall temperature. The discussion of results begins on Page 4-31 and wall temperature comparisons are shown in Figures 4.2 and 4.3 on Page 4-32 in EMF-2100(P).

- <u>FLECHT-SEASET Test 33056</u> – Test 33056 is used to assess the Sleicher-Rouse heat transfer coefficient to vapor. The key parameters are void fraction, mass inventory, steam temperatures, differential pressure, heat transfer coefficients, and wall temperatures. The discussion of results begins on Page 4-32 and wall temperature comparisons are shown in Figures 4.4 and 4.5 on Page 4-33.

- Marviken Tests 22 & 24 – The tests assess the S-RELAP5 critical flow model. Since Moody is used for Appendix K analysis, these tests are not applicable to SBLOCA. The key parameters are pressure, fluid temperature, and mass flow (break). The discussion of results begins in Section 5.1.3.2 and comparisons with data are shown in Figures 5.6 through 5.10 on Pages 5-28 through 5.32.

- UPTF Tests 6 & 7 – These tests were designed to quantify downcomer ECC bypass during the blowdown phase (accumulator injection phase) of a LBLOCA. The tests are also used to show 2-Dimensional effects in the downcomer inlet annulus region. The key parameters are differential pressure and mass in lower plenum. The discussion of results begin in Section 5.5.2 and gas velocity profiles are shown in Figure 5.17 on Page 5-60.

- UPTF Test 11 – The test assesses hot leg CCFL at the steam generator inlet. The test is run under SBLOCA conditions and the phenomena are applicable to SBLOCA. The key parameters are mass flow rate and CCFL. The discussion of results begin in Section 5.5.3 and comparison with data is shown in Figure 5.19 on Page 5-64.

The experiments listed below are the additional tests used specifically for SBLOCA. Included are lists of key parameters assessed. The tests are documented in EMF-2328(P):

- 2-Dimensional Flow Problems – A set of three steady state flow problems in a bundle test section. The flow was partially blocked in one of the two bundles, providing 2-Dimensional flow data for assessing 2-Dimensional codes. This problem is used to assess the S-RELAP5 2-Dimensional model. The key parameters are pressure drops and velocities. The results are discussed in Section 5.1.

- Semiscale Test S-UT-8 – This is a small scale test that investigated the effects of downcomer to upper plenum bypass on SBLOCA. The significant phenomena observed was a deep, long core level depression and subsequent heat-up prior to loop seal clearing. The portion of the transient used for assessment was the period of core heat-up prior to loop seal clearing and CCFL. The key parameters are cladding temperatures, pressure histories, mass flows, and liquid levels. The results are discussed in Section 5.2.

- LOFT LP-SB-3 – A SBLOCA test with a nuclear core. HPSI was not activated in order to instigate a core heat-up. Upon reaching designated cladding temperatures, a 'feed and bleed' process was activated in the steam generators to bring the system pressure down to accumulator injection pressure, thus terminating the experiment. The heat-up portion of this test was used to assess the dryout wall heat transfer, level model, and the 2-Dimensional model. The key parameters are cladding temperatures, pressure histories, and liquid levels. The results are discussed in Section 5.3.

- UPTF Loop Seal Clearing Test – A separate effects test to show loop seal clearing behavior under typical SBLOCA conditions. This test was used to assess loop seal clearing and horizontal stratified flow. The key parameters are pressure drops and liquid levels. Results are discussed in Section 5.4.

- BETHSY Test 9.1.b – A small scale (1/100 volume, full height) SBLOCA test with 3 loops. HPSI was not instigated to cause core heat-up. Upon reaching designated temperature, steam generators were blown down to atmospheric conditions to bring primary pressure down to accumulator injection pressure. The accumulator injection quenches the core. The experiment was continued past core quenching to show a second loop seal clearing. This test was used to assess relevant SBLOCA phenomena, including loop seal clearing (including second clearing), core heat-up, core quenching, and CCFL. The key parameters are cladding temperatures, pressure histories, pressure drops, mass flows, and liquid levels. The results are discussed in Section 5.5.

The following tests are used to assess the non-LOCA capability and are discussed in EMF-2310(P), Sections 4.2 through 4.5:

- LOFT L6-1 – Loss of load
- LOFT L6-2 – Loss of primary flow.
- LOFT L6-3 – Excessive steam load.
- LOFT L6-5 – Loss of feedwater.

Non-LOCA transients are integral tests that are event focused rather than S-RELAP5 constitutive model focused. The assessments therefore identified that the general system behavior in the simulation was physical (e.g. in a heatup transient, does the coolant expand and the pressurizer level rise? Does the power in the reactor core decrease? etc.). That being the case, the following information was considered important in the LOFT non-LOCA simulations:

- SG Level
- Pressurizer Level
- Pressurizer Pressure
- SG Pressure
- Reactor Power
- Hot Leg Temperature
- Cold Leg Temperature
- SG Steam Flow Rate
- FW Flow Rate (L6-3)
- RCS Flow Rate (L6-2)
- RCP Speed (L6-2)

At a fundamental level these few key parameters characterize the mass and energy in the system.

The additional tests listed below are part of the STS, but were not documented in EMF-2100(P). They are used for S-RELAP5 model assessment. The tests are listed with brief descriptions and the key parameters are identified:

- MIT Pressurizer – The test is used to validate the level model. The key parameters are pressure and liquid level.

- FLECHT-SEASET Tests 31504 – Test 31504 is used to assess dry-wall interphase drag and reflood wall heat transfer. The key parameters are void fraction (or differential pressure), steam temperatures, mass inventory, heat transfer coefficients and wall temperatures. Figures 2 to 8 show some examples of code-data comparisons. The results of the time-step and nodalization study depicted in Figures 6 to 8 are important for validating the flow regime transition regions and criteria. The main purpose of flow regime classification is to provide smooth transitions between different sets of correlations. The physical phenomena are mainly determined by the constitutive correlations used. Step-changes in interphase interaction terms often produce oscillations and distort the solution. Correlations are of little value if a relatively smooth solution can not be obtained. For a system code such as S-RELAP5, the applicability of the flow regime classification is primarily measured by how harmoniously different correlations work together. Therefore, the most important factors in determining the transition criteria and the extent of the transition region are appearance of smooth solutions, number of repeated time steps, time-step and nodalization sensitivities, and mass error. The interphase heat transfer correlation of Equation (3.134) is mainly responsible for the good comparison between measured and calculated steam temperatures shown in Figure 2. With respect to Figure 3, the interphase friction correlation for the inverted-slug flow sets the amount of liquid in the quench front region. The calculated differential pressure indicates that more liquid is present in neighborhood of the quench front region. This is consistent with the lower wall temperatures before quench, as shown in Figures 6 and 7. Due to numerical diffusion inherent with the donor scheme, it is difficult to spread out the liquid in a longer range, which may occur in the experiment. By keeping more liquid in the inverted slug region, a lower amount of liquid is in the upper elevations. This results in good code-data comparison of wall temperatures in the temperature-rise period. As PCT occurs in the temperature-rise period, it is significant that the code has the capability to properly calculate the thermal-hydraulic responses far above the quench front. Figure 8 shows that the calculated maximum temperature points are distributed in the outer envelope of the data points and that the spread due to time step and nodalization sensitivity is much smaller than the spread of data. The interphase friction package is responsible for the bundle mass displayed in Figure 4.

Figure 2. Steam Temperatures Calculated at 6.3 feet and Measured at 6 feet for FLECHT-SEASET Test 31504

Figure 3. FLECHT-SEASET Test 31504 Calculated and Measured Differential Pressures Between 6 and 7 feet.

Figure 4. FLECHT-SEASET Test 31504 Total Mass in the Bundle

Figure 5. FLECHT-SEASET Test 31504 Heat Transfer Coefficients

Figure 6. Calculated Rod Surface Temperatures at 6.6 feet for 20 Volume Core Cases with Various Time Step Sizes for FLECHT-SEASET Test 31504. The Solid Curve is the Data

Figure 7. Calculated Rod Surface Temperatures at 6.6 feet for 40 Volume Core Cases with Various Time Step Sizes for FLECHT-SEASET Test 31504. The Solid Curve is the Data

Figure 8. Code-Data Comparison of Maximum Clad Temperatures vs. Axial Elevation for FLECHT-SEASET Test 31504

- LOFT Tests L2-5 & L2-6 – These tests are used to assess the LBLOCA capability of S-RELAP5. Several phenomena that occur during these tests can be used to assess various models that are also used in SBLOCA. These include phenomena associated with ECC injection (subcooled water injected into superheated steam), horizontal stratification, and interphase condensation. The key parameters are cladding temperatures, pressure histories, mass flows, density, fluid temperatures, and liquid levels.

  Examples of code-data comparisons of key parameters for LOFT 2-6 and L2-5 are shown in Figures 9 to 26. The agreements are in general good. The calculated results are plotted as a solid line and the measured data are plotted as a dashed line.

Figure 9. LOFT L2-6 Broken Hot Leg Mass Flow Rate

Figure 10. LOFT L2-6 Intact Loop Cold Leg Mass Flow Rate

Figure 11. LOFT L2-6 Broken Cold Leg Density

Figure 12. LOFT L2-6 Upper Plenum Fluid Temperatures

Figure 13. LOFT L2-6 Lower Plenum Fluid Temperatures

Figure 14. LOFT L2-6 Intact Loop Hot Leg Fluid Temperatures.

Figure 15. LOFT L2-6 Pressurizer Collapsed Liquid Level

Figure 16. LOFT L2-6 Primary and Secondary Pressures

Figure 17. LOFT L2-6 Central Bundle Cladding Temperatures (Solid Pellet) at 27.5 in.

Figure 18. LOFT L2-5 Broken Loop Hot Leg Mass Flow Rate

Figure 19. LOFT L2-5 Broken Loop Cold Leg Mass Flow Rate

Figure 20. LOFT L2-5 Broken Cold Leg Density

Figure 21. LOFT L2-5 Upper Plenum Fluid Temperatures

Figure 22. LOFT L2-5 Lower Plenum Fluid Temperatures

Figure 23. LOFT L2-5 Intact Loop Hot Leg Fluid Temperatures

Figure 24. LOFT L2-5 Pressurizer Collapsed Liquid Level

Figure 25. LOFT L2-5 Primary and Secondary Pressures

Figure 26. LOFT L2-5 Central Bundle Cladding Temperatures (Solid Pellet) at 27.5 in.

- <u>2-D Symmetric Fill</u> – This is a simple model with an analytic solution that can be determined visually (by inspection of printed or plotted velocities) for assessing the 2-Dimensional model (see response to Question 2.2). The key parameters are velocities and liquid levels.

- <u>CCTF – Run 54</u> – This is an integral test to show the LBLOCA capability of S-RELAP5. Several phenomena that occur during these tests can be used to assess various models that are also used in SBLOCA. These include phenomena associated with ECC injection (subcooled water injected into superheated steam), horizontal stratification, interphase condensation, and core heat-up. The key parameters are cladding temperatures, pressure histories, mass flows, mass inventory, differential pressures, void fraction, and liquid levels. Examples of code-data comparisons for some key parameters are shown in Figures 27 to 32. The calculated results are generally in good agreement with the data. Note particularly that the condensation in the cold leg during the ECC injection period is well calculated, as shown in Figure 29. During the short period of accumulator injection, both calculated results and measured data indicate that the cold leg is almost full of liquid (part from ECC injection and part from condensation of steam). During the LPCI injection period, the amount of liquid is too small to be measured accurately by the instrument.

Figure 27. CCTF Test Run 54 Pump-Side Break Mass Flow Rate

Figure 28. CCTF Test Run 54 Intact Loop Hot Leg Mass Flow Rates

Figure 29. CCTF Test Run 54 Intact Loop Cold Leg Void Fraction

Figure 30. CCTF Test Run 54 Downcomer Differential Pressure

Figure 31. CCTF Test Run 54 Core Differential Pressure

Figure 32. CCTF Test Run 54 Heater Rod Surface Temperatures around the Mid-Plane for High Power Bundles

3.3 *(This question is related to large break LOCA (LBLOCA) only and may be responded to at the time of the BE LBLOCA submittal.)*

On Page 3-1, last paragraph, it is stated that the Electric Power Research Institute (EPRI) drift-flux correlations used in RELAP5/MOD3 are tuned mostly to the steady-state data with regular flow profiles and that there is little evidence that these fix-profile correlations produce good results in simulating LBLOCA transients which are highly irregular and chaotic in nature. It is also stated that the EPRI correlations do not cover the entire range of two-phase flow conditions. Based on this information, it was stated that S-RELAP5 did not adopt the same approach as used in RELAP5/MOD3 but that assessment examples are presented to show that the S-RELAP5 two-fluid formulation produces code-data comparisons that are as good as those obtained by RELAP5/MOD3 for steady-state and nearly steady-state cases. Since the concern stated with the EPRI drift-flux correlations was with the modeling of the LBLOCA transients which are highly irregular and chaotic in nature, please provide the assessments that were performed to ensure that the correlations used in S-RELAP5 are adequate for highly irregular and chaotic transient cases.

This question will be responded to as part of the NRC review of the SPC Realistic PWR LBLOCA model (to be submitted).

3.4 *In Equation 3.7, you limited α_L to a minimum value of 0.1 and used $(D^*/19)^8$. Which experiments form the basis for choosing these values? Please justify the use of these values.*

As explained in the paragraph after Equation (3.7), $(D^*/19)^8$ is a way to convert a discontinuous transition criterion of Equation (3.3) into a mathematically continuous formulation. In reactor applications, D^* is either much greater than 19 or much smaller than 19; therefore, there is no practical difference between Equation (3.3) and $(D^*/19)^8$. The smaller diameter criterion of Equation (3.3) is mainly applicable to the core in the reactor systems. The core hydraulic diameter is sufficiently small to preclude the presence of the bubbly flow regime. For computational reasons, a narrow region of bubbly flow is required to provide a smooth transition between single phase liquid and slug flow. Historically, values such as 0.02, 0.05 and 0.1 have been used to define a small region of bubbly flow. There are no apparent ill effects from using any one of the values mentioned above. The value of 0.1 is chosen to provide consistency in the transformation of bubbly flow to inverted annular flow (see RAI question 3-23) since a reactor core is the only component where the dry-wall flow regimes may be of significance. Assessments of ORNL THTF Level Swell Tests, LOFT L2-5, L2-6, FLECHT-SEASET 31504 and CCTF Run 54 validate the use of these values (see data comparisons shown in response to Question 3.2).

3.5 *Please describe the tests used in the assessment and provide the assessments performed to validate the use of Equation 3.11 and the limits provided in the text that follows the equation on Page 3-6 and 3-7 in relation to the $\alpha_{S\text{-}A}$ criteria.*

Equation (3.11) is an empirical relation based on theoretical consideration and experimental observation. The justifications for using the relationship of Equation (3.11) are discussed on Pages 3-5 and 3-6. Jones and Zuber (Reference 3.12) experimentally determined that the transition between slug flow and annular flow occurs around a void fraction of 0.8. The separate-effects tests that may be sensitive to this flow regime transition criterion and, therefore, indirectly validate the criterion are: GE 1ft Level Swell Test 1004-3, UPTF Test 11, and Marviken Critical Flow Tests (co-current down flow). Assessment results of tests such as LOFT L2-5 and L2-6, Semiscale Test S-UT-8, UPTF Loop Seal Clearing Test, and Bethsy Test 9.1b also depend on the transition criterion (see data comparisons shown in response to Question 3.2).

3.6 *On Page 3-7, end of the first paragraph, it is stated that introduction of transition regions may reduce the chances of occurrence and magnitude of discontinuities in interphase interaction terms, but it can not completely eliminate the discontinuities. Please describe known discontinuities that still remain and how these are dealt with in the coding of S-RELAP5.*

By incorporating transition regions, there are no mathematical discontinuities between flow regimes. The statement was referring to the evaluation of an interphase interaction terms at successive time-steps where flow conditions are such that different flow regimes are calculated to occur. The resulting values from the interphase interaction terms may differ greatly, appearing to be computationally discontinuous. The effect of these large differences may reduce the quality of the data comparison or cause oscillations of undetermined magnitude. In general, decreasing the time-step size reduces the computational difference between successive time-step interphase interaction terms. However, reducing the time-step size does not guarantee that the computed differences will be sufficiently small so to not affect the quality of the comparison or reduce oscillations to negligible magnitudes.

The last sentence in the paragraph will be rephrased as follows to clarify its meaning:
It should be cautioned that introduction of transition regions may reduce the chances of occurrence of step-changes in magnitude of interphase interaction terms, but it cannot completely eliminate them.

3.7 *Please describe the information used to confirm the validity of the interpolation in Equation 3.15.*

The intent of Equation (3.15) is to bridge two different sets of constitutive equations. The proof of its effectiveness is mainly measured by sensitivities in time-step and nodalization sizes. The FLECHT-SEASET Test 31504, CCTF Run 54, and THTF Level Swell tests (see response to Question 3.2) were used specifically for assessing Equation (3.15). The parameters used for determination of acceptable performance were void fraction and transition to dryout.

3.8 *Under the vertical stratification section starting on Page 3-8, there appear to be no flow/velocity criteria established for when vertical stratification may occur. Please explain how vertical stratification is detected.*

The detection logic for vertical stratification is described on Pages 3-8 to 3-10. The essential point is that there is a sharp void fraction increase in a consecutive three vertical volume stack. Such a condition usually can not be established under high flow conditions. Therefore, it is redundant to include velocity/flow criteria. Nevertheless, for computational efficiency, the detection of vertical stratification is not performed for mass fluxes greater than 1500 kg/m^2s. This is simply a filter to exclude the circumstances where Equations (3.16) and (3.17) are nearly impossible to be satisfied.

3.9 *Please describe how the mixture level model described under the vertical stratification section was validated.*

The mixture level model is most critical for handling a condensation process. Under condensation conditions, the mixture level usually becomes a liquid level. The model is validated by 1-D and 2-D fill problems (see response to Question 2.2), the MIT pressurizer problem (qualitatively), and the LOFT non-LOCA Tests (pressurizer behavior). For flashing or boiling conditions, the mixture level provides only a small enhancement on phase separation. For flashing cases with insignificant wall-to-fluid heat transfer, the rapid decrease of interphase friction with increasing void fraction is sufficient, by itself, to produce a sharp mixture level. The assessment of the GE 1ft Level Swell Test validates the mixture level under flashing conditions. Within the PWR applications, the mixture level for the boiling cases is dominated by the transition from pre-CHF to post-CHF heat transfer. The sharp gradient in void fraction is produced by the transition from slug flow to mist (dispersed) flow. The model under such circumstances is validated by ORNL THTF Level Swell Tests, FLECHT-SEASET Test 31504, CCTF Run 54, LOFT L2-5 and LOFT L2-6 (see data comparisons shown in response to Question 3.2).

3.10 *Please describe the assessment performed to justify the method used for the transition region between the stratified and non-stratified flow (i.e., Equation 3.26 and associated restrictions and criteria).*

The primary test used for developing the transition region criteria was the UPTF Loop Seal Clearing test (see response to Question 3.2). Time-step size sensitivities were used to introduce perturbations due to apparent discontinuities between the interfacial drag for horizontal stratified and bubbly/slug flow (see response to Question 3.6). Since the vapor flow exceeded the stable flow criteria and was in the transition region, this process is an acceptable method determining transition region criteria. The acceptance criteria for determining the transition region was consistent liquid levels in the horizontal section when using time step sizes of 5 milliseconds to 100 milliseconds.

3.11 *Justify the choice of 0.9 for j_g* for the boundary between slug and annular mist flow (Equation 3.28) in light of the wide range of 0.25 to 1.0 suggested by Wallis. What are the sensitivities of the results of the analyses of interest to the value of j_g* and why is 0.9 appropriate in light of these sensitivities? What is the range of hydraulic diameters that this criterion is valid for? Please describe the assessment performed to cover the sensitivity to hydraulic diameter. Provide a comparison to applicable experimental data.*

The flow regime classification is an intermediate model necessary and convenient for providing a reasonable approximation of evaluating the interphase friction and interphase heat transfer. High precision of flow regime transition criteria is not warranted since the uncertainty of interphase friction is large. The inclusion of large region of transition before the annular flow boundary further diminishes the importance of the transition line criterion.

For the US PWR plants and their related test facilities, the main horizontal components are hot legs and cold legs. In the case of SBLOCA, the cold legs and hot legs are in bubbly flow during the early period. The flow regime then changes to and stays in the horizontal stratification flow since the vapor velocity is low. All other horizontal flow regimes play no role; therefore, the precision of the annular flow transition criterion is immaterial. For LBLOCA, the annular flow can appear in the hot legs for a short duration (about 2 sec) during the very early period of blowdown when the void fraction is higher than 0.8 and the pressure is still rather high. Under such circumstances, the limit value of 0.8 overwrites the J_g^* criterion. As soon as the pressure decreases and the density ratio of liquid to vapor increases to around 500, the flow regimes of both cold and hot legs become horizontally stratified. At liquid-vapor density ratio of 500, void fraction of about 0.8 and typical hot leg diameter of about 0.75 m, Equation (3.23) yields a critical vapor velocity of $v_{HS} \approx 40 m/s$. The interpolation scheme used in the transition region [see Equation (3.65)] suggests that the horizontal stratification may be dominant at least up to half of the transition region, i.e., up to vapor velocity of about 70 m/s. Considering the vapor velocity is about 50 m/s during the refill period and about 30 m/s during the reflood period, the horizontal stratified flow is still the most important flow regime in the horizontal components for LBLOCA. Thus, for LOCA, the annular flow in the horizontal component either plays no role or is insignificant; therefore, there is no need to consider the dependency of hydraulic diameter or to determine an accurate value of J_g^*. It should be pointed out, however, that the high value of 0.9 is more appropriate for J_g^*. Since the annular flow can only be present at very high vapor velocity, a low value of J_g^* will yield a void fraction too low to be considered as annular flow.

There are no appropriate data for a direct assessment of flow regime criteria. The assessment can only be performed on the whole constitutive package, not individual pieces. The horizontal constitutive package is validated through examining mass flow rate, fluid density, fluid temperature and void fraction in cold legs and hot legs for LOFT L2-5, LOFT L2-6, CCTF Run 54, and UPTF Test 11 (see data comparisons shown in response to Question 3.2).

3.12 *Please describe how the effect of condensation at the ECCS injection point is handled in S-RELAP5.*

The effect of condensation at the ECCS injection point is generically treated by the condensation mass transfer model, including Equations such as (3.115), (3.116), (3.123), (3.142) and (3.148). There is no special ECCS component or model.

3.13 *Please show how Equation 3.23 is derived from the material in the reference. Also, it appears in Equation 3.23 that the α_g is a subscript to β. Please confirm or correct this.*

3.14 *On Page 3-48, it is stated that various assessment calculations indicate that Equations 3.98 and 3.99 function well. Please identify and discuss the tests that were used in the assessment calculations and the results of the assessment calculations.*

The purpose of Equations (3.98) and (3.99) is to bring any metastable state to as close to the saturation state as possible to prevent unforeseeable numerical difficulties caused by large departure of superheated liquid or subcooled steam state from the saturation state. The term "function well" simply means that the purpose is achieved. All metastate temperatures are close to the saturation and there are no state failures in any assessment calculation. This is a numerical necessity, as explained on Page 3-47. Except for Marviken Critical Flow Tests, there are no experimental data exhibiting effects caused by highly superheated liquid or highly subcooled vapor and the code does not calculate any of them. As for the Marviken Tests, the break flow data show an extremely short period of sudden drop and rise of break flow [see Figure 5.6 on Page 5-28 of EMF-2100(P)] due to the presence of highly superheated liquid right after the break is initiated. The code does not calculate such a sharp drop and rise in break mass flow rate, but the period is too short to be of any significance.

3.15 *Section 3.4.8 discusses the equilibrium option that exists in S-RELAP5. Please provide a table showing when (i.e., in what transient analyses) this option would be allowed and when it would not be allowed. Also, please provide a reference to the section in the user's manual that directs the user to follow these restrictions. If allowed in any of the licensing analyses, please justify the values selected.*

The equilibrium option is not and has not been used in SPC assessment and licensing analysis calculations. The need for guidelines has not been necessary since the code will not run with the option turned on.

3.16 *Section 3.4.9 discusses the effect of noncondensables on condensation rate. Please justify your use of Equations 3.169 and 3.165 in S-RELAP5 to handle the reduction of condensation rate in the presence of noncondensables. Please provide a description and results of assessment calculations that justify the use of these equations.*

The effects of noncondensables on interphase condensation appear in LBLOCA. The tests used for assessment are LOFT tests L2-5 and L2-6. In those tests, subcooled safety injection initiates in the approximate time frame as the accumulator empties of liquid and injects nitrogen into the system. Thus, subcooled liquid is injected into a two-phase mixture with noncondensables present.

The safety injection is delivered to the primary system from a constant head pump which makes the flow dependent on downstream pressure. Under the system conditions with subcooled liquid injected into superheated steam, condensation would occur, causing a slight pressure decrease which would further increase the injection rate. The reduction in condensation due to nitrogen injection from the accumulator increases the downstream pressure and thus reduces the injection rate. Therefore, LPSI flow rate is a key parameter for assessing the effects of condensation with noncondensables present.

From Figure 33, the measured LPSI flow shows a short period of decreased flow indicating that the pressure had increased during that period. The reason for the short period of increased pressure/decreased flow was the decrease in condensation due to the presence of noncondensables.

In S-RELAP5, the LOFT L2-6 LPSI is modeled with a time dependent junction specifying flow as a function of downstream pressure (simulating a constant head pump). As shown in Figure 33, the calculated and measured LPSI initially agree well. Subsequently the calculated LPSI flow rate decreases for a short period when an increasing flow is expected, following the trends measured during the experiment. This comparison shows the effects of Equations (3.165) and

(3.169). The comparison also shows the reduction in condensation is underestimated. This assessment case is used primarily for LBLOCA validation.

Figure 33. Comparison of S-RELAP5 LPSI Flow with Measured Data from LOFT Test L2-6

3.17 *For time smoothing, it is stated on Page 3-68 that the scheme implemented in S-RELAP5 is empirical and that various assessment calculations indicate that it works satisfactorily. Please describe the assessment calculations performed for confirming the time smoothing scheme. In addition, show how the assessment calculations provide a test for the scheme.*

Any test where mass transfer effects dominate the calculated results can be used to demonstrate the effectiveness of the smoothing algorithm. Upon completion of model development, the GE Level Swell Test [see Page 3-43 of EMF-2100(P)] was used to study the effects of mass transfer time smoothing, Equations (3.171) through (3.174). The criteria used for determining the constant in Equation (3.172) was the assumption that fewer repeated time-steps implies a smoother transient.

3.18 *In Section 3.4.10, in relation to mass error, it is stated that S-RELAP5 implements a strategy which forces only condensation to take place when the amount of liquid in a volume is small and subcooled and the vapor is superheated. In addition, this strategy forces only evaporation to take place when the amount of vapor in a volume is small and subcooled and the liquid is superheated. It is stated that these limits have no significant effects on physical results as one would expect from such a diminishing amount of liquid or vapor and that these limits reduce mass error substantially. Please justify your strategy for dealing with the mass error. In your justification, please discuss any assessments that were performed, the tests used in the assessments, and the results.*

3.19 *In Section 3.4.10, in relation to subcooled nucleate boiling, it is stated that S-RELAP5 implements a strategy which lowers the interphase heat transfer coefficients in order to eliminate situations where the total mass transfer rate, Γ_g, becomes negative. Please justify your strategy for dealing with this situation. In your justification, please discuss any assessments that were performed, the tests used in the assessments, and the results. In addition, the last paragraph on Page 3-70 states that there is no guarantee that the final solution at the end of each time step meets all the conditions or limits described in the section. Please explain what is meant by this statement and explain and justify what is done in S-RELAP5 when the conditions or limits are not met.*

The rationale and method for the special treatment of vapor generation under subcooled boiling conditions are discussed on Pages 3-69 to 3-70. In general, the sum of bulk mass transfer (condensing) and wall vapor generation is positive (.i.e., vaporizing) when the wall temperature is above the net-vapor-generation point and the scheme is not applied. However, mismatched conditions may be calculated at times. Mismatched conditions may be ignored or corrected. The treatment used for correcting the model inconsistency in subcooled nucleate boiling is designed to improve the quality of the numerical solutions, such as smoothness in space/time, reducing the number of repeated time steps, and reducing the mass error. The effect on the liquid temperature due to the adjustment of bulk condensation rate to be smaller than the wall vaporization rate is extremely insignificant. The scheme is intended to enhance the numerical performance of the code without affecting significantly the overall physical results. Therefore, its only validation is that the code is numerically performing well on all calculations; i.e., extremely rare code failures, no excessive number of repeated time steps, no appreciable mass error, etc. This is the case. Also, there is no code problem caused by condensation in a subcooled nucleate boiling volume, as it used to be years ago. The table shown in the response to Question 3.18 confirms that this scheme (strategy) together with other special numerical treatments for the mass transfer model produces very good mass conservation in S-RELAP5.

All special treatments discussed in this section are based on old time (i.e., at the beginning of the current time step) information. As shown in Equation (2.197), the new time (i.e., at the end of the time step) vapor generation rate is obtained from the old time vapor generation rate by including the contributions from changes of pressure, liquid energy, vapor energy, and noncondensable quality within the time step. The new time vapor generation rate (part of the final solution) may not satisfy all the conditions or limits imposed by the special treatments. As no check is made on whether any inconsistency is still present at the end of time step, there is no guarantee that the final solution meets all the conditions or limits. However, it is expected that even if some conditions are not met, the discrepancy is not significant enough to cause appreciable solution truncation error. In any case, the final solution is checked against the time-step control criteria described in Section 2.6.7 to ensure solution convergence.

3.20 *Please provide a list of the figures of merit and important phenomena in relation to each of the transients and accidents to be analyzed with S-RELAP5. Please also describe how these figures of merit and important phenomena were designated as important for the relevant analyses.*

In addition to 10.CFR 50.46 requirements of PCT and maximum cladding oxidized, the time histories of the following parameters are reported with a SBLOCA analysis:

- Primary and secondary pressure
- Reactor power
- Core level
- Core collapsed liquid level
- Total primary system mass
- Break mass flow rate
- Void fraction at the break junction
- Combined delivered SI flow
- Combined accumulator flow
- PCT node vapor temperature
- PCT node clad surface temperature
- Rupture node clad surface temperature (only if rupture occurs)
- Steam generator liquid level
- Void fraction in the last node of the loop seal (RCP side)
- Steam velocity in the loop seal
- Metal-water reaction information

A review of the behavior of the above parameters as a function of time is performed to assure that the analysis produces expected results. The choice of those parameters was confirmed by an informal PIRT that was developed to identify important phenomena with respect to SBLOCA transient period. A summary of the results of the informal PIRT for the SBLOCA event is shown in Table 2 below.

3.21 *In Sections 3.4.1 through 3.4.7 heat transfer correlations, limits on these correlations, and transition equations are presented for different flow regimes. However, no justifications are provided. Please provide justifications for the material presented in these sections and provide discussion of assessments performed to confirm the adequacy of correlations used in S-RELAP5.*

The limits on the interpolation parameters for smoothing are Equations (3.103), (3.114), (3.119), (3.124), (3.136) and (3.150). They define the transition region between two correlations of different valid ranges, for example, a subcooled correlation and a superheated correlation. In the transition region, they have the values between 0 and 1. They usually can and do take the value of either 0 or 1 to select one of the correlations. Many of the limits are simply the maximum of two correlations. They include Equations (3.101), (3.123), (3.146), (3.151), and (3.159). The approach is standard. The rest are limits placed on the phasic velocities. These are in Equations (3.125), (3.142), (3.144) and (3.148). They are numerical necessities to filter out fluctuations in code-calculated phasic velocities. They were put in to improve reliability of the code calculations.

The limits and the correlations work together as an integral package. Some of the assessments that justify/validate the mass transfer constitutive package are LOFT L2-5, LOFT L2-6, CCTF Run 54, ORNL THTF Level Swell Tests and FLECHT-SEASET 31504 (see data comparisons shown in response to Question 3.2). From LOFT L2-5 and L2-6 assessments, code data comparisons are performed on fluid temperatures at various locations, and density comparisons in cold and hot legs. In CCTF Run 54, the cold leg void fraction is a good test for the condensation model. The ORNL THTF Level Swell Tests assess the subcooled nucleate boiling model. Code-data comparisons of steam temperatures for the FLECHT-SEASET test validates the vaporization model for superheated steam. Also, the depressurization rates in blowdown calculations such as the LOFT tests and Marviken Critical Flow Tests are affected by the vaporization model of superheated liquid.

3.22 *Page 3-11, last paragraph, it is stated that "...some calculations with RELAP5/MOD2 indicated that the range of stratified flow is too small. Kukita et al suggested that the vapor velocity on the left side of Equation 3.22 be replaced by the relative velocity (v_g-v_f). This approach along with an additional constraint to exclude high mass flux conditions was implemented in the previous S-RELAP5 code versions. Recent experience with small break test cases and plant calculations indicated that the new approach might increase code variability. Therefore, the approach of replacing the vapor velocity with relative velocity is abandoned."*

Since the approach was abandoned, what was done to address the concern that the range of stratified flow was too small and how was that justified? Please provide comparisons of your approach to data to justify the adequacy of your approach.

The concern needs to be addressed because RELAP5/MOD3 uses similar approach (i.e., relative velocity and a mass flux criterion). The information is useful for the code developers so that they know the approach was tried once. Actually, the range of stratified flow defined by Equation (3.23) is not small at all for the diameter size of typical PWR hot and cold legs. This can be seen from Fig. 6 of Reference 3.3 (Taitel's paper). The region of stratified flow expands substantially with increasing diameter. The response to Question 3.11 also shows that the range of stratified flow is rather large under typical LBLOCA conditions of hot and cold legs. For PWR SBLOCA, with Equation (3.23) the flow regime in the cold/hot legs stays always in the stratified flow, but not so with the approach using relative velocity plus an additional constraint. The assessments of LOFT L2-5 and L2-6, CCTF Run 54 and UPTF Test 11 show that Equation (3.23) is applicable to both large and small diameters (see data comparisons shown in response to Question 3.2).

3.22 (*This question is related to LBLOCA only and may be responded to at the time of the BE LBLOCA submittal.)*

For dry-wall flow regimes, please justify your use of 0.1 for the α_{IA-IS} criterion in light of the information provided in the text preceding Equation 3.13 that indicates that the transformation of the three wet-wall flow regimes into inverted annular, inverted slug, and mist flow regimes should be used.

In US reactor applications, the classification of dry-wall flow regimes is really required only in the core. As discussed in response to Question 3.4, the bubbly flow boundary for the core is set at void fraction of 0.1 to be consistent with the α_{IA-IS} criterion.

Chapter 4: Heat Transfer Models

4.1 *In reviewing Section 4, Heat Transfer Models, it is apparent that this section is totally different to any comparable heat transfer section in RELAP5/MOD2. Contributions from various known sources constitute the basis for this heat transfer model.* Please provide qualitative (and quantitative) *justification for the formulation of this particular heat transfer model. (i.e., assumptions, mass flow rates, pressure, enthalpy, etc.).*

Most heat transfer correlations in S-RELAP5 are inherited from RELAP5/MOD2 with or without minor modifications. In the code manual, the RELAP5/MOD2 heat transfer equations are written for the heat transfer rates into hydro volumes, while the S-RELAP5 heat transfer equations are expressed in terms of the heat flux and heat transfer coefficient. The boundary conditions for the conduction solution scheme are expressed in terms of heat transfer coefficients and heat fluxes in both RELAP5/MOD2 and S-RELAP5. The selection logic for heat transfer regimes is somewhat simplified in S-RELAP5, but the regimes are essentially the same in both codes.

Equation (4.1) is a general expression for total heat in the RELAP5 series of codes, including RELAP5/MOD2 and S-RELAP5. The same is true for the heat transfer coefficients, Equation (4.2). Note that not all of the terms in Equations (4.1) and (4.2) may be present for a given heat transfer regime, as explained on Page 4-1. For example, the subcooled nucleate boiling heat transfer is described in S-RELAP5 by Equation (4.15):

$$q'' = h_{mac}(T_w - T_f) + h_{mic}(T_w - T_{sat}) .$$

The heat transfer to the vapor phase is not present, i.e., h_{cg} of Equation (4.1) is zero. The same heat transfer equation is documented in RELAP5/MOD2 (RELAP5/MOD2 Code Manual Volume 1: Code Structure, Systems Models, and Solution Methods, NUREG/CR-4312, Rev. 1, March 1987, Page 109) as

$$Q_{wf} = \left[h_{mic}\,\Delta T_{sat} + h_{mac}\left(T_w - T_f\right)\right]A_{wf} / V$$
$$Q_{wg} = 0$$

The terms inside the square brackets of the above equation are the same as those on the right side of Equation (4.15) of S-RELAP5. Also the correlations for h_{mic} and h_{mac} are the same for both codes. In general, there are no differences between RELAP5/MOD2 and S-RELAP5 in heat transfer modeling schemes and principles.

4.2 *On Page 4-2 of the S-RELAP-5 Models and Correlations Code Manual, the last sentence of the last paragraph discusses the issue of reflood being turned off and on. Who decides when or where the option is turned on or off at the appropriate time?*

The reflood model is an input option, which can be selected by the user for some particular heat structures. If the option is selected, the user also has the option to set the time to start the model. The users' manual, RELAP5 Input Data Requirements, EMF-CC-097(P), Revision 4, describes the general recommendations for setting the starting time of the reflood model, but the specific procedures will be stated in the methodology guidelines. For SBLOCA and non-LOCA transients, the reflood model is not used. For LBLOCA applications, the user must follow the LBLOCA methodology guidelines.

4.3 *Please provide an explanation of the difference between the data and the calculational results in Figure 4.3.*

The discrepancy is explained on Page 4-31 of EMF-2100(P). It should be pointed out that this particular case is outside the range of reactor accident applications because the mass flux in the post-CHF regimes under accident conditions will never reach such a high value of 3797.4 kg/m^2-s.

4.4 *How does RELAP-5/MOD2 or MOD3 compare to the same data as that presented in RAI 4.3 above? A comparison of S-RELAP5 and RELAP5/MOD2 against the data and on the same page would help.*

Figure 34 shows measured data and the calculated results from S-RELAP5, ANF-RELAP and RELAP5/MOD3.2. "5379_Calc" is the same as shown in Figure 4.3 in EMF-2100(P) for S-RELAP5, "5379_ANFR" is from ANF-RELAP, which should yield the same result as RELAP5/MOD2, and "5379_MOD3.2" is from RELAP5/MOD3.2. The ANF-RELAP code produces the best post-CHF results because the under-prediction of vapor convective heat transfer is compensated by the use of the modified Bromley correlation at high void fraction (higher elevations). {Note: on Page 113 of the RELAP5/MOD2 manual, it indicates that Dougall-Rohsenow is used. This is incorrect. In all of the released versions of RELAP5/MOD2 and MOD3, the factor $(1-\alpha_g)v_f$ is not included in the vapor phase convective heat transfer computation.} As discussed on Pages 4-16 to 4-18 of EMF-2100(P), two correlations (Forslund-Rohsenow dispersed film boiling and modified Bromley) are used for the film boiling heat transfer in S-RELAP5. This yields much lower film boiling heat transfer than RELAP5/MOD2 at higher elevations where the void fraction is high. In RELAP5/MOD3, a multiplication factor is applied on the modified Bromley correlation to reduce the heat transfer coefficient to liquid at the high void fractions. Therefore, the temperature trend at higher elevations is very similar for S-RELAP5 and RELAP5/MOD3.2.

Figure 34. Comparison of RELAP5 Versions

Chapter 11: Point Kinetics Model

11.1 *On Page 11-16, the last equation has a term missing. The term " $\boldsymbol{-V_{01}}$ " is missing. Compare with Equation 7.6-21 in NUREG/CR-5535, V1.*

Concur. The code manual EMF-2100(P) will be corrected.

The following question is in regard to Topical Report EMF-2328(P) Revision 0:

SB.1 *Please justify use of 0 percent fuel clad preoxidation in the SBLOCA analysis.*

The SPC methodology described in EMF-2328(P), "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based," results in a conservative calculation of peak local oxidation for comparison to the 17% oxidation criteria of 10 CFR 50.46. The methodology assumes that the pre-accident cladding oxidation is zero in order to maximize the rate and extent of oxidation during a LOCA. This assumption results in higher peak cladding temperatures and higher peak local oxidation than assuming a non-zero pre-accident oxidation value.

Cladding oxidation from two sources is considered: (1) pre-accident or pre-transient oxidation due to corrosion at operating conditions, and (2) transient oxidation which occurs at high temperature during the LOCA. Pre-transient oxidation is determined by a fuel performance calculation and is a function of burnup. Over the burnup range that the fuel rod is at high power and can approach technical specification peaking limits, the pre-transient oxidation is small; however, at high burnups, pre-transient oxidation can become significant.

Transient oxidation is calculated as part of the LOCA analyses. By rule, this oxidation must be computed using the Baker-Just reaction rate equation. Using this equation, the calculated reaction rate decreases in direct proportion to the increase in thickness of the layer oxidized and increases exponentially with absolute temperature. Therefore, the transient oxidation is maximized by minimizing the initial oxidation layer which yields the highest reaction rate. The increased reaction rate produces higher temperatures which further increases the reaction rate, thus compounding the effect.

The reason that the assumption of zero pre-accident oxidation value results in a conservative calculation of peak cladding temperature and total peak local oxidation is that SPC's calculations show that a non-zero pre-accident oxidation assumption reduces the transient oxidation by an amount greater than the pre-accident oxidation. Therefore, the maximum oxidation; i.e., the sum of both pre-transient and transient oxidation is greatest when zero pre-transient oxidation is assumed. These results apply for conditions where the transient oxidation is the dominant contributor to the total oxidation, which is the case for calculated PCTs in excess of 2000°F and for burnups at which peaking can approach the technical specification limits. These are the most limiting cases for both LBLOCA and SBLOCA.

SPC also recognizes that conditions exist where the total oxidation is dominated by the pre-transient oxidation. This situation occurs when lower PCTs are calculated and at high burnups. For cases with low PCTs, the pre-accident oxidation becomes dominant because the transient oxidation is substantially reduced or effectively eliminated due to the low absolute temperature. For high burnups, the transient oxidation is reduced or effectively eliminated due to the inherent low power and associated low transient temperatures, and is further reduced by the presence of a significant initial oxide layer. For these cases, the maximum total oxidation is essentially equal to the initial pre-accident oxidation value. This oxidation value can exceed the value calculated using a zero initial pre–accident oxidation for these conditions; however, the total oxidation is precluded from approaching or exceeding the 17% value by the design limit on pre-accident oxidation. **[**

]

EMF-2328(NP)(A)
Revision 0

PWR Small Break LOCA Evaluation Model, S-RELAP5 Based

January 2000

Nature of Changes

Item	Page	Description and Justification
1.	All	This is a new document.

Abstract

A Pressurized Water Reactor (PWR) Small Break Loss of Coolant Accident (SBLOCA) Emergency Core Cooling System (ECCS) evaluation model is presented that incorporates S-RELAP5 as the systems analysis code. A fuel rod model based on the NRC approved RODEX2 code has been integrated into S-RELAP5 to calculate the fuel rod heat-up portion of the SBLOCA. The revised evaluation model replaces the NRC approved evaluation model defined by Reference 1 which utilized the ANF-RELAP and TOODEE2 codes for system analysis and hot rod heat up.

A number of benchmark cases have been analyzed to demonstrate that S-RELAP5 is capable of modeling a SBLOCA. The benchmarks consist of two-dimensional flow tests, the Semiscale S-UT-8 test, the LOFT LP-SB-03 test, a loop seal clearing test in the UPTF, and an integral test in the BETHSY facility. In addition, an example problem is provided to demonstrate the application of the evaluation model.

Contents

Tables

Figures

Nomenclature

Acronym	Definition
AFW	auxiliary feedwater
ANF	Advanced Nuclear Fuels
ANS	American Nuclear Society
ASCE	American Society of Chemical Engineers
ASME	American Society of Mechanical Engineers
CCFL	counter-current flow limiting
CE-EPRI	Combustion Engineering – Electric Power Research Institute
CFR	Code of Federal Regulations
CHF	critical heat flux
ECC	emergency core coolant
ECCS	emergency core cooling system
EOC	end of cycle
HHSI	high head safety injection
ICAP	International Code Assessment Program
INEEL	Idaho National Engineering and Environmental Laboratory
INEL	Idaho National Engineering Laboratory
ISP	International Standard Problem
KWU	Kraftwerk Union
LBLOCA	large break loss of coolant accident
LHSI	low head safety injection
LOCA	loss of coolant accident
LOCES	Loss-of-Coolant Evaluation Studies
LOF	loss-of-feedwater (or loss-of-fluid)
LOFT	Loss of Fluid Test
MSCV	main steam control valve
MSSV	main steam safety valve
NAI	Numerical Application Inc.
NRC	United States Nuclear Regulatory Commission
PCS	primary cooling system
PCT	peak clad temperature
PWR	pressurized water reactor
RCP	reactor coolant pump

SBLOCA	small break loss of coolant accident
SIAS	safety injection actuation signal
SPC	Siemens Power Corporation
TMI	Three-Mile Island
TRAM	Transient Analysis Method
UPTF	Upper Plenum Test Facility

1.0 Introduction

Siemens Power Corporation (SPC) plans to use the S-RELAP5 (Reference 2) code for analysis of small break loss of coolant accidents for Westinghouse and Combustion Engineering PWRs. The NRC has previously reviewed and accepted the SPC methodology using the ANF-RELAP and TOODEE2 codes for small break LOCA analysis for PWRs (Reference 1). The revised evaluation model is an evolutionary outgrowth of SPC's existing methodology and conforms to the requirements for ECCS analysis set forth in 10 CFR 50.

The objective in using S-RELAP5 is to apply a single, advanced, industry recognized code for all analyses, including LOCA and non-LOCA events. Using a single code that has had extensive review permits the development of one base input deck for the analysis of all events for a particular application. The benefits of using a single code include ease of use by engineers, reduced maintenance requirements on developers, improved quality of both code and applications, and reduction of resources for the NRC review of associated methodology.

S-RELAP5 is a modification of ANF-RELAP. The modifications were made primarily to accommodate large and small break LOCA modeling. A hot rod model has been incorporated within the S-RELAP5 code itself. The hot rod model includes fuel models from the approved fuel design code, RODEX2 (References 3 and 4) and the approved swelling and rupture model (Reference 5) from the hot rod model code TOODEE2. The hot rod heat-up calculation is performed as part of the S-RELAP5 system calculation resulting in a single, consistent calculation using one code.

2.0 Summary

The purpose of this report is to document and demonstrate the adequacy of a revised SPC methodology using S-RELAP5 for performing SBLOCA analysis. The code and component models were benchmarked against test data to demonstrate the acceptability of the models for SBLOCA analysis. An example plant calculation was performed to estimate the effects of the new model in licensing situations and to provide a base calculation for sensitivity studies. Finally, sensitivity studies were performed using the example calculation to demonstrate the code stability and the methodology insensitivity to typical modeling changes encountered during analysis.

Section 3.0 presents a detailed description of the SBLOCA scenario and describes the methodology using S-RELAP5 and its application. The description emphasizes the phenomenology determining the outcome of the event.

Section 4.0 describes the model changes made to ANF-RELAP that create the S-RELAP5 SBLOCA evaluation model. The S-RELAP5 code includes changes to the following:

- Multi-dimensional capability
- Energy equations,
- Numerical solution of hydrodynamic equations
- Equation of state for steam in a non-condensable mixture
- Hydrodynamic constitutive models
- Heat transfer model
- Choked flow
- Counter-current flow limiting
- Component models
- Fuel model.

Section 5.0 presents the validation benchmark cases for the SBLOCA evaluation model. These benchmark cases use comparisons with measured test data and sensitivity studies to validate the SBLOCA model. The tests used specifically for SBLOCA assessment are:

- Two-dimensional bundle tests with flow blockage
- The Semiscale S-UT-8 test
- The boil-off portion of the LOFT LP-SB-03 test

- A loop seal clearing test performed in the Upper Plenum Test Facility (UPTF)
- The BETHSY 9.1b small break test (ISP-27)

Results from the two-dimensional validation cases demonstrated the general capability of S-RELAP5 to predict two-dimensional flow phenomena in these single-phase tests. The Semiscale S-UT-8 and LOFT LP-SB-3 benchmarks are validations retained from the previous SBLOCA model submittal and demonstrate high pressure, low velocity heat transfer and reflux condensation. Comparisons with the UPTF loop seal clearing test shows that S-RELAP5 conservatively predicts this important event for SBLOCA analysis. The BETHSY integral test demonstrates the capability of S-RELAP5 to predict the overall SBLOCA behavior and to yield conservative temperature results.

An example calculation for a three-loop Westinghouse PWR is presented in Section 6.0. This calculation demonstrates the methodology and provides the base case used for sensitivity studies.

Table 2.1 shows the results from the example calculation using the revised model and similar results using the currently approved SBLOCA evaluation model (Reference 1). The PCT result is similar to the earlier licensing calculations.

Table 2.1 Comparison Between Previous and Proposed Methodologies

Methodology	**PCT (°F)**	**Maximum Local Oxidation (%)**
S-RELAP5, 2-inch break (new)	1634	1.1
Approved model, 2-inch break (old)	1649	3.0

Using the example base case plant input, sensitivity study calculations were performed for the following:

- Time step size
- Restarting
- Loop seal biasing
- Pump model
- Radial flow loss coefficients
- Nodalization

PCT results from the sensitivity studies are shown in Table 2.2. The results show that the S-RELAP5-based SBLOCA methodology is well converged and has a small sensitivity to all the parameters investigated. The sensitivity of the previous model to radial flow loss coefficients does not exist for the new methodology; therefore the requirement to perform sensitivity calculations in licensing analysis on this parameter is eliminated from the new methodology.

Table 2.2 Sensitivity Studies Summary

3.0 Small Break LOCA Evaluation Model Description

3.1 *Event Description*

Loss of coolant accidents (LOCAs) are defined as postulated accidents that would result from the loss of reactor coolant, at a rate in excess of the capability of the normal reactor coolant makeup system, from piping breaks in the reactor coolant pressure boundary. The piping breaks are postulated to occur at various locations and include a spectrum of break sizes. Loss of significant quantities of reactor coolant would prevent heat removal from the reactor core, unless the water is replenished. General Design Criterion 35 requires each PWR to be equipped with an Emergency Core Cooling System (ECCS) that refills the vessel in a timely manner to satisfy the requirements of the regulations for ECCS given in 10 CFR Part 50, §50.46 and Appendix K to 10 CFR Part 50.

The postulated SBLOCA is defined as a break in the PWR primary coolant system pressure boundary having a break area equal to or less than 10 % of the cross sectional area of the cold leg or vessel inlet pipes. This range of break areas encompasses the range of penetrations in the primary system boundary. Small breaks can involve relief and safety valves, charging and letdown lines, drain lines and instrumentation lines.

3.1.1 Limiting Break Conditions

There are several locations at which the break could occur. The break location that produces the greatest challenge to the acceptance limits is in the cold leg pipe at the discharge side of the pumps. Breaks at higher elevations will change from liquid to steam flow much sooner and will lose inventory much less rapidly. The discharge side of a pump results in the greatest pressure drop between the core exit and the top of the downcomer, thereby depressing the core level and increasing the period of core uncovery. The limiting break size, which produces the highest PCT, depends on the ECCS. For C-E plants, it is generally in the neighborhood of 2 % of the cold leg pipe area. For Westinghouse plants, it can be less than 1 %.

Immediately after the break, the primary coolant system (PCS) undergoes a rapid de-pressurization with a reactor trip occurring when the pressure falls to the low-pressurizer pressure trip setpoint. The safety injection actuation signal occurs when the PCS pressure reaches the safety injection actuation signal setpoint, which is usually lower than the reactor trip setpoint. This signal initiates operation of the ECCS. Only the HHSI system will deliver flow initially. The LHSI will not activate for this event, as the system pressure will always exceed the LHSI shut-off head. For most break sizes, the PCS pressure will usually eventually fall below the accumulator pressure. The flow from the accumulator terminates the challenge to the acceptance limits.

The principal ECCS component mitigating all break sizes is the HHSI and the worst single failure is usually the assumed loss of a diesel generator, which results in disabling of one HHSI pump and one motor driven auxiliary feedwater pump. Typically, a limited number of HHSI pumps are allowed to be out of service for maintenance. Most often, only one HHSI pump is assumed available for each analysis. A delay for the start-up of the emergency diesel generator is included in the HHSI system response.

SBLOCA transients fall into one of three categories, depending on the size of the break in the PCS. The smallest breaks are characterized by inventory losses that are less than the flow from the HHSI pump. In this case, core uncovery is insignificant and there is little, if any, heat-up of the fuel. The largest breaks are characterized by a rapid de-pressurization of the PCS. In this case, PCS pressure falls rapidly to the accumulator pressure and both core uncovery and hot rod heatup are limited. HHSI pumps have a limited effect for this category of SBLOCA.

Intermediate breaks are generally the most limiting because the rate of inventory loss from the primary system is large enough that the HHSI pumps cannot preclude significant core uncovery. The slow de-pressurization of the PCS extends the time required to reach the accumulator pressure and can even result in the pressure remaining above the accumulator pressure. The duration of the uncovery is maximized by a break in this intermediate range. During uncovery the heat transfer from the hot rod is limited and the decay heat causes the uncovered portion of the rod to heat up.

The break size and the configuration and capacity of the ECCS are the dominant factors that dictate the SBLOCA transients. The auxiliary feedwater (AFW) system is also a factor, with the effect becoming more pronounced as the break size is decreased. For plants where charging pumps are considered safety grade, charging pump flow may be included with the ECCS flow. Therefore, depending upon plant design and geometry, differences in limiting break size can occur. For some plants the limiting break size can be much larger than for others.

The peak cladding temperature is expected to occur at End of Cycle (EOC) burnup conditions. This is due to the dominant effect of a top-skewed EOC axial power distribution and a larger actinide decay heat at EOC.

3.2 *Limiting Break Scenario*

The phenomena which occur during the small break LOCA event have been studied and reported in Reference 6. The SBLOCA scenario developed during this process was for a Westinghouse 4-loop PWR, but because of the similarity of design features is also applicable to PWRs of 3-loop Westinghouse design as well as Combustion Engineering (CE) designed PWRs.

The small break transient is characterized by five time periods: blowdown, natural circulation, loop seal clearance, boil-off, and core recovery. While the duration of each period is break size and system dependent, the small break LOCA transient can be described as follows:

Blowdown: On initiation of the break, there is a rapid decompression of PCS. Reactor trip is initiated on a low pressurizer pressure setpoint. Pump trip occurs either automatically based on the assumption that off-site power is lost coincident with the reactor trip or as a result of operator action. A safety injection signal occurs when the primary pressure decreases below the pressurizer low-low pressure setpoint, and safety injection flow begins after a signal delay time. The PCS remains liquid solid for most of the blowdown period, with phase separation starting to occur in the upper head, upper plenum, and hot legs near the end of this period. During the blowdown period, the break flow is single-phase liquid only. Eventually the rapid depressurization ends when the PCS reaches a pressure just above the steam generator secondary side pressure.

Natural Circulation: At the end of the blowdown period, the PCS reaches a quasi-equilibrium condition which can last for several hundred seconds depending on break size. During this period the loop seals remain plugged and the system drains top down with voids beginning to form at the top of the steam generator tubes and continuing to form in the vessel upper head and top of the vessel upper plenum region. Decay heat is removed by the steam generators during this time. Vapor generated in the core is trapped within the PCS by liquid plugs in the loop seals, and a low quality flow exits at the break. This period is referred to as the natural circulation period.

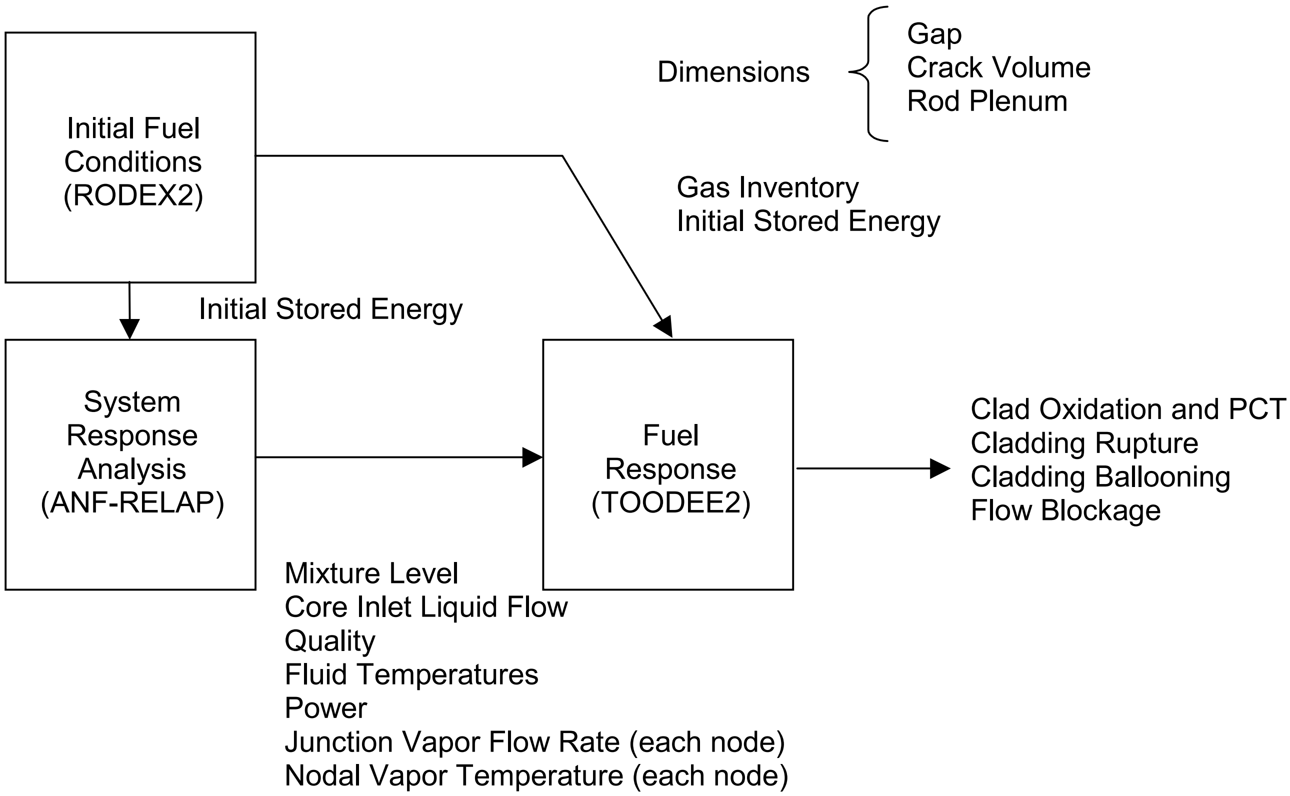
Loop Seal Clearance: The third period is the loop seal clearance period When the liquid level in the downhill side of the steam generator is depressed to the elevation of the top of the horizontal loop seal piping, steam previously trapped in the PCS can be vented to the break. The break flow, previously a low quality mixture, transitions to primarily steam. Prior to loop seal venting, the inner vessel mixture level can drop rapidly, resulting in a short core uncovery. Following loop seal venting, the core recovers to about the cold leg elevation, as pressure imbalances throughout the PCS are relieved.

Boil-Off: Following loop seal venting, the vessel mixture level will decrease. In this period, the decrease is due to the boil-off of the liquid inventory in the reactor vessel. The mixture level will reach a minimum, in some cases resulting in a deep core uncovery. The boil-off period ends when the core liquid level reaches this minimum. At this time, the PCS has depressurized to the point (usually the accumulator setpoint) where ECC flow into the vessel matches the rate of boil-off from the core.

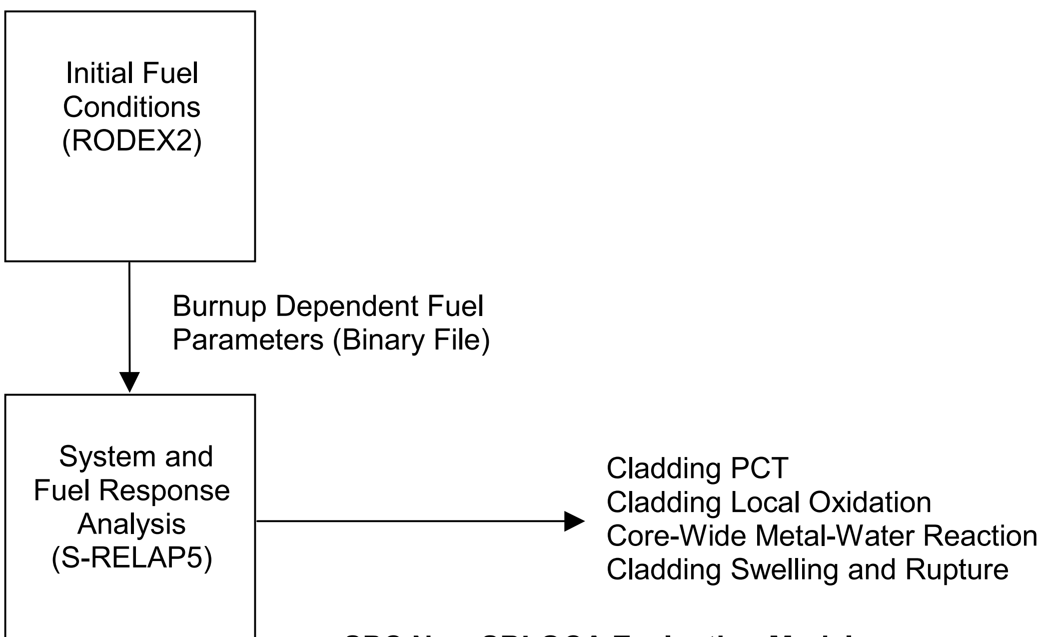
Core Recovery: The core recovery period extends from the time at which the inner vessel mixture reaches a minimum in the boil-off period, until all parts of the core quench and are covered by a low quality mixture. The small break LOCA is considered over, and the calculation is terminated when the temperature transient in the core has been terminated, and the safety injection flow exceeds the break flow.

3.3 ***Methodology Description***

Two principal computer codes are used to analyze the SBLOCA event. Initial conditions as a function of fuel burnup for the hot rod and the core are calculated using RODEX2 to determine the effects of exposure on the fuel and rod properties. The SBLOCA transient response is calculated using S-RELAP5, which in addition to calculating the overall response, also calculates the hot rod temperature transient using the RODEX2 fuel models and the NUREG-0630 swelling and rupture models embedded in the code. Figure 3.1 schematically shows the simplification made to the methodology by incorporating RODEX2 and TOODEE2 models into S-RELAP5. The hot rod calculations are described in Section 4.0.



SPC Old SBLOCA Evaluation Model



SPC New SBLOCA Evaluation Model

Figure 3.1 Schematic of Old and New SPC Small Break Models

3.3.1 System Modeling

All of the PCS loops and the SGs in the S-RELAP5 model of a plant are explicitly modeled to enhance the accuracy of the calculation. A typical SBLOCA S-RELAP5 reactor vessel nodalization and loop piping for a 3-loop Westinghouse plant is illustrated in Figure 6.1. The nodalization for steam generator secondary system is depicted in Figure 6.2. Deviation from this nodalization would be necessary for plants that have the SI system directly connected to the cold legs or other geometrical differences from the example PWR.

The reactor primary and secondary coolant systems are modeled. Primary system modeling includes: the pressurizer, reactor coolant pumps, hot- and cold-leg piping, the reactor vessel and internals, the steam generator, the accumulators, and the HHSIs. Secondary modeling includes the steam generator secondary, feedwater, isolation valves, relief valves, and steam lines. Generally, the nodalizations are fairly conventional, with the exception of components that can have a large effect on the SBLOCA outcome. The components for which special modeling approaches were used are discussed next.

3.3.1.1 Loop Seal Modeling

The loop seal region begins at the exit of the steam generator and ends at the entrance to the pump impeller region. Modeling of the loop seal region is important for breaks in the cold-leg piping located downstream of the pump discharge. Details of loop seals vary between plant designs. The similarity between loop seals designs is that they consist of a descending piping segment connected from the steam generator exit plenum to a horizontal piping segment. The horizontal piping is then connected to an ascending piping segment which connects to the reactor coolant pump.

[

]

The horizontal and ascending segments are each modeled with single volumes. [

]

The ascending section responds to carry-over from the horizontal section. Modeling this as a single volume results in relatively smooth behavior and provides agreement with tests performed at the Upper Plenum Test Facility (Reference 7). The testing and comparisons are discussed in Section 5.4 below.

[

]

3.3.1.2 Main Coolant Piping

Each piping loop of the PCS is modeled separately. The components of each loop include the following:

- hot-leg piping
- a pressurizer (if applicable)

- the steam generator inlet plenum
- the steam generator tubes
- the steam generator exit plenum
- the cross-over piping from the steam generator to the pump (loop seal)
- the primary coolant recirculation pump
- an accumulator or safety injection tank
- ECCS connections
- the cold leg piping from the pump to the vessel

3.3.1.3 Reactor Coolant Pumps

The pumps have a number of different effects on the SBLOCA as the event progresses. Initially, when they are operating and coasting down, they provide flow to the core and raise the pressure at the break location. This increased pressure reduces the reactor vessel coolant inventory prior to loop seal clearing. After the pumps coast down, they constitute an additional resistance in the vent path for the steam from the core. The pump pressure drop is calculated from the pump speed and the pump performance data in the form of homologous head and torque curves. Since the lowest point of the pump discharge to the cold leg is usually elevated above the bottom of the cold leg, the pumps also inhibit HHSI flow from flowing backward into the loop seal. [
]

[
]

3.3.1.4 Downcomer Modeling

[

]

3.3.1.5 Upper Vessel

During the period in which the upper vessel region is losing liquid inventory, the region between the core exit and the hot legs will interact with the core. [

]

3.3.2 Core Modeling

The behavior of the liquid mixture level in the hot region surrounding the hot rod is the most significant factor in SBLOCA. Although most influenced by other models, the core liquid mixture level can be affected by the modeling of the core itself.

3.3.2.1 General Hydraulic Modeling

[

]

3.3.2.2 Radial Loss Coefficients

[

]

3.3.2.3 Heat Structures

[

]

3.4 *SBLOCA Analysis*

The purpose of the SBLOCA analysis is to demonstrate that the criteria stated in 10 CFR 50.46(b). These criteria are as follows:

1) The calculated maximum fuel element cladding temperature shall not exceed 2200°F.

2) The calculated local fuel rod cladding oxidation shall nowhere exceed 17% of the total cladding thickness before oxidation.

3) The calculated total amount of fuel element cladding which reacts chemically with water or steam shall not exceed 1% of the Zircaloy within the heated length of the core.

4) The cladding temperature transient shall be terminated at a time when the core geometry is still amenable to cooling.

5) The core temperature shall be reduced and decay heat shall be removed for an extended period of time, as required by the long-lived radioactivity remaining in the core.

S-RELAP5 is the principal computer code used for analysis of the SBLOCA event. Before the analysis can be performed, S-RELAP5 requires initial fuel rod conditions. The rod conditions are calculated by RODEX2 where the fuel burn-up is taken to the desired burnup, usually end of cycle conditions. The RODEX2 results at the desired burnup are transferred to S-RELAP5. A steady state calculation using S-RELAP5 is made that initializes the system model to plant operating conditions. After assuring the steady state calculation is representative of the plant operating conditions, the SBLOCA transient is performed. In addition to calculating the overall system thermal-hydraulic response, S-RELAP5 also concurrently calculates the hot rod temperature transient using the hot rod input including RODEX2 fuel models and the NUREG-0630 swelling and rupture models which were taken from the implementation in the TOODEE2 code.

After calculations and analysis have been made to determine the limiting single failure, a break spectrum is analyzed by making several calculations with varying break sizes. From this calculational set, the results are examined to determine the break size having the greatest PCT or maximum oxidation present. The calculation having the greatest PCT or maximum amount of cladding oxidized in the break spectrum is the limiting SBLOCA break yielding the reportable PCT, and becomes the analysis of record. The results of this analysis are also compared to the criteria in 10 CFR 50.46(b) for reporting purposes.

The results from the sample problem, discussed Section 6.0, shows that little variation in calculated PCT occurs with small changes to the model. Because of this demonstrated convergence, additional sensitivities are not required to be performed during licensing analysis.

4.0 Model Description

The S-RELAP5 (Reference 2) code includes hydrodynamic models, heat transfer and heat conduction models, a fuel model, a reactor kinetics model, control system models, and trip system models. S-RELAP5 uses a two-fluid, nonequilibrium, nonhomogeneous, hydrodynamic model for transient simulation of the two-phase system behavior. The hydrodynamics include many generic component models: pumps, valves, separators, turbines, and accumulators. Also included are the special process models: form loss at an abrupt area change, choked flow, and counter-current flow limiting (CCFL) models.

The S-RELAP5 code evolved from SPC's ANF-RELAP code, a modified RELAP5/MOD2 version (Reference 8), used at SPC for performing PWR plant licensing analyses including small break LOCA analysis, steam line break analysis, and PWR non-LOCA Chapter 15 event analyses. The code structure for S-RELAP5 was modified to be essentially the same as that for RELAP5/MOD3 (Reference 9), with the similar code portability features. The coding for reactor kinetics, control systems and trip systems were replaced with those of RELAP5/MOD3. The majority of the modifications to S-RELAP5 were undertaken to improve its applicability for the realistic calculation of Large Break LOCA (LBLOCA). To a large extent, those models are relevant to analysis of PWR SBLOCA events.

In Section 1.1 of the S-RELAP5 Models and Correlations Manual (Reference 2) there is a list summarizing major modifications and improvements in S-RELAP5. Where appropriate, this list is reproduced herein with additional information specific to SBLOCA.

1) <u>Multi-Dimensional Capability</u>. Full two-dimensional treatment was added to the hydrodynamic field equations. The two-dimensional capability can accommodate the Cartesian and the cylindrical (z,r) and (z,θ) coordinate systems, and can be applied anywhere in the reactor system. Thus far, SPC has applied two-dimensional modeling to the downcomer, core, and upper plenum. The RELAP5/MOD2 cross-flow modeling also was improved. The application of a two-dimensional component in the downcomer is important for simulating the asymmetric emergency core cooling (ECC) water delivery observed in the UPTF downcomer penetration tests (Reference 10).

2) <u>Energy Equations</u>. The energy equations of RELAP5/MOD2 and RELAP5/MOD3 have a strong tendency to produce energy error when a sizeable pressure gradient exists

between two adjacent cells (or control volumes). This deficiency is a direct consequence of ignoring specific energy terms that are difficult to approximate numerically. Therefore, the energy equations were modified to conserve the energies transported into and out of a cell. For analyses involving containment modeling, the new approach is more appropriate numerically. For SBLOCA calculations, no significant differences were calculated in the key parameters such as clad surface temperature, break mass flow rate, void fraction, and others between the two formulations of the energy equations.

3) Numerical Solution of Hydrodynamic Field Equations. The reduction of the hydrodynamic finite-difference equations to a pressure equation is obtained analytically by algebraic manipulations in S-RELAP5, but is obtained numerically by using a Gaussian elimination system solver in RELAP5/MOD2 and MOD3. This improvement aids computational efficiency and helps to minimize effects due to machine truncation errors.

4) State of Steam-Non-Condensable Mixture. Computation of state relations for the steam-noncondensable mixture at very low steam quality (i.e., the ratio of steam mass to total gas phase mass) was modified to allow the presence of a pure noncondensable gas below the ice point (0°C). The ideal gas approximation is used for both steam and noncondensable gas at very low steam quality. This modification is required to correctly simulate the accumulator depressurization and prevents spurious code failures during accumulator ECCS water injection. For SBLOCA, this model does not have significant impact.

5) Hydrodynamic Constitutive Models. Significant modifications and enhancements were made to the RELAP5/MOD2 interphase friction and inter-phase mass transfer models. The constitutive models are flow-regime dependent and were constructed from the correlations for the basic elements of flow patterns such as bubbles, droplets, vapor slugs (i.e., large bubbles), liquid slugs (i.e., large liquid drops), liquid film, and vapor film. When possible and applicable, literature correlations were used as published. Often a constitutive formulation is composed of more than one correlation to cover different flow regimes. Transition flow regimes were introduced to allow a smooth change between two constitutive models. Partition functions for combining different correlations and for

transitions between two flow regimes were developed based on physical reasoning and code-to-data comparisons. Most of the existing RELAP5/MOD2 partition functions were retained in S-RELAP5. The vertical stratification model implemented in ANF-RELAP was further improved. The RELAP5/MOD2 approximation to the Colebrook equation of wall friction factor was replaced by the more appropriate explicit-approximate formulation of Jain (Reference 11).

6) Heat Transfer Model. The use of a different set of heat transfer correlations for the reflood model in RELAP5/MOD2 was eliminated. Some minor modifications were made to the selection logic for heat transfer modes (or regimes), single phase liquid natural convection and condensation heat transfer. The Lahey correlations for vapor generation in the subcooled nucleate boiling region were implemented (Reference 12). No changes are made to the RELAP5/MOD2 CHF correlations. [

]

7) Choked Flow. The computation of the equation of state at the choked plane was modified. Instead of using the previous time step information to determine the state at the break, an iterative scheme is used. This modification was also implemented in ANF-RELAP. Some minor modifications were also made to the under-relaxation scheme to smooth the transition between subcooled single phase critical flow and two-phase critical flow. The Moody critical flow model (Reference 14) is also implemented and used for Appendix K SBLOCA analyses.

8) Counter-Current Flow Limiting. The Kutateladze-type CCFL correlation in ANF-RELAP was replaced by the more general Bankoff form (Reference 15), which can be reduced to either a Wallis-type or a Kutateladze-type CCFL correlation. RELAP5/MOD3 also uses the Bankoff correlation form (Reference 16).

9) Component Models. SPC's pump performance degradation model developed from CE-EPRI data was included in the S-RELAP5 pump model. The computation of pump head in the fluid field equations was modified to be more implicit. A containment model was added. With this model, the containment pressure boundary conditions are provided by the approved EXEM/PWR evaluation model code, ICECON, which is run concurrently

with S-RELAP5 using realistic values for parameter input. The accumulator model was eliminated because of its well-known problems. With S-RELAP5, the accumulator is to be modeled as a pipe with nitrogen or air as noncondensable gas. The ICECON containment model is not used in SBLOCA transient analyses.

10) Pump Modeling. [

]

11) Fuel Model. The RODEX2 fuel model and the NUREG-0630 clad ballooning and rupture model, as implemented in TOODEE2, have been incorporated into the S-RELAP5 code to calculate the fuel response for transient analyses. Both models have been approved for licensing applications (References 3, 4 and 5). The Baker-Just metal-water reaction model (Reference 18) is used for oxidation during the transient. The oxidation level is set to zero at the start of the transient for the metal-water reaction calculation. The oxidation reported for comparison to the criteria is that calculated with the Baker-Just model and does not include pre-transient oxidation. The S-RELAP5/RODEX2 model does not calculate the burnup response of the fuel. Instead, fuel conditions at the burnup of interest are transferred from RODEX2 to S-RELAP5 via a binary data file from a separate RODEX2 calculation. The data transferred from RODEX2 describes the fuel state at zero power before the transient. A steady-state S-RELAP5 calculation is

required to establish the fuel state at power, which is approximately the same as RODEX2 fuel state at the same power. The clad ballooning and rupture model also accounts for flow diversion in the vicinity of the rupture location in the same way as the TOODEE2 code.

5.0 Benchmark Calculations

The S-RELAP5 code was applied to two separate effects and three integral tests to validate code performance under SBLOCA conditions. The tests are summarized in Table 5.1. The tests were chosen to specifically test the two-dimensional model, loop seal clearing, and core heat transfer.

Table 5.1 Experiment Summary

Experiment	Description	SBLOCA Relevancy
2-D Flow Tests	Separate effects test with parallel 14x14 bundles, full width, partial height, with one bundle blocked and various flows in the other.	Two-dimensional core model
Semiscale S-UT-8	Scaled PWR integral facility, test series designed to investigate effects of ECCS on SBLOCA.	Core heat-up before loop seal clearing
LOFT LP-SB-3	Scaled PWR integral test facility, test series designed to study core heat transfer during slow boil-off SBLOCA (1.84 inch equivalent).	Core heat transfer during boil-off phase
UPTF-A5RUN11E	Full-scale PWR test facility, test series designed to study loop seal clearing behavior with vapor super heat.	Loop seal clearing
BETHSY Test 9.1b	Scaled PWR integral test facility, test series designed to study SBLOCA without HHSI.	Integral effects: 2-inch equivalent small break, three-loop facility, loop seal clearing

From the table, the applicability range covers relevant break sizes, loop seal clearing, and core heat-up for scenarios of interest.

5.1 *Two-Dimensional Flow Test*

This benchmark calculation compares the two-dimensional component in S-RELAP5 with test data and verifies that the two-dimensional component in S-RELAP5 can be used to model multidimensional flow problems. The tests selected for this comparison are a series of flow blockage tests using test assemblies prototypic of 14x14 Westinghouse assemblies.

5.1.1 Test Facility Description

The test data selected for comparison was used to benchmark XCOBRA-IIIC, VIPRE, and THINC-IV (References 19 and 20) for both core flow redistribution and flow redistribution within a single fuel assembly. The original test data is reported in a Westinghouse Advanced Reactor Division document: E. Weiss, *Flow Recovery in a Blocked Fuel Assembly*, ARD-TH-416, October, 1969, the results of which are summarized in Reference 20 and, for subsequent testing by Weiss for a similar configuration, in Reference 21.

The test configuration for both sets of tests by Weiss is shown in Figure 5.1.1. For the bulk of the testing, the gap between the two simulated fuel assemblies was left open (Figure 5.1.2). For the Reference 21 testing, a perforated plate was inserted between the two simulated fuel assemblies (Figure 5.1.3).

The tests consisted of introducing asymmetric flow in the inlet region and measuring flow recovery in the bundle. The test reported in Reference 21 also had the outlet of one assembly blocked. Because of the detail of the measurements and the nearly prototypic geometry, the test results from Reference 20 have become a standard benchmark test for flow redistribution codes.

Reference 20 reported the results for two test configurations in sufficient detail to allow comparison. Nominally, the first configuration has 1100 gpm entering one fuel assembly and 550 gpm in the other. The second configuration has one inlet blocked and 1500 gpm entering the other. In both cases, the exits are open.

The case discussed in Reference 21 is similar, but has a perforated plate inserted between the two assemblies, the inlet and outlet blocked on one assembly, and a nominal total flow of 1300 gpm.

5.1.2 S-RELAP5 Model Description

Models for the test section and the boundary conditions for each of three tests were constructed based on the geometry shown in Figure 5.1.1 through Figure 5.1.3. Using the models, local velocities and flows were calculated to compare to the data. A simplified nodalization diagram is given in Figure 5.1.4.

[

]

5.1.3 Boundary Conditions

[

]

5.1.4 Comparison to Data

References 20 and 21 present axial velocity distribution maps at six different elevations for three tests. The assembly without blockages is Assembly A.

- The inlet flow for Assembly A was nominally 1100 gpm and 550 gpm for Assembly B.
- The inlet flow for Assembly A was nominally 1500 gpm and the inlet to Assembly B was blocked.
- The inlet flow for Assembly A was nominally 1300 gpm and both the inlet and outlet to Assembly B were blocked.

5.1.4.1 Test 1 – 1100/550

Figure 5.1.6 through Figure 5.1.11 compare the reported axial fluid velocities for the test with an inlet flow of 1100 gpm in one side (A) and 550 gpm in the other (B) to those calculated by S-RELAP5. The data for this flow comparison as extracted from Figure 4.3 of Reference 20. The THINC-IV fit starts with a flow split at the zero elevation that has 69% of the flow in Assembly A. This would be a flow split of 1138/512 gpm with the same total flow. Based on the comparisons to the THINC-IV code, the flow split was really much closer to 1138 to Assembly A and 512 to Assembly B. Test 1 was run using these values.

The comparison of flow velocities at the pitot tube locations with the S-RELAP5 calculations shows, with minor exceptions, excellent agreement. The axial flow fractions are compared in Figure 5.1.12 and also compare well to the data.

5.1.4.2 Test 2 – 1500/0

Figure 5.1.13 through Figure 5.1.18 compare the reported axial fluid velocities for the test with an inlet flow of 1500 gpm on side A and with side B blocked at the inlet to those calculated by S-RELAP5. A calculation of total mass flow, calculated by integrating the velocity profiles, was used to deduce the correct flow for the test. Based on a comparison of the integrated velocity distribution with the integrated S-RELAP5 velocity distribution, the flow split at the inlet should really be about 1281/0 gpm. The comparisons are based on this adjusted value. S-RELAP5 calculates reverse flow near the back wall of the blocked assembly (B). The test data shows reverse flow, or the possibility of reverse flow, with zero velocities from the pitot tubes. The S-RELAP5 results, with minor exceptions are in very good agreement with the measured data.

Figure 5.1.19 compares the reported mass flow fraction in assembly A with that calculated by S-RELAP5. The agreement for this test is not as good as that for the case with the 1100/550 gpm flow split. The points of largest disagreement are Levels 4 through 7. The velocity measurements at these levels did not conserve total mass flow, therefore the difference between the S-RELAP5 predictions and the data may well be much smaller in this region than Figure 5.1.19 indicates.

5.1.4.3 Test 3 – 1300/0

Reference 21 reports a similar test, using the same test rig with a perforated plate inserted between the two test assemblies (Figure 5.1.3). Figure 5.1.20 through Figure 5.1.25 compare the reported axial fluid velocities for this test to those calculated by S-RELAP5. The agreement for these data is reasonably good for all levels. Again, the most significant difference is the ability of S-RELAP5 to calculate reverse flow in the blocked assembly.

5.1.5 Comparison to Core Flow Distribution Codes

To assess the quality of the comparison to data, the XCOBRA-IIIC and THINC-IV flow predictions for the test were compared to the S-RELAP5 flow predictions. XCOBRA-IIIC was benchmarked against one case; the case from Reference 20 that had an inlet flow split of 1100/550 gpm.

The THINC-IV fit was extracted from Figure 4.3 of Reference 20. As noted, the flow split for THINC-IV was closer to 1138/512 gpm. The XCOBRA-IIIC benchmark case was run with the inlet flows adjusted for this change in flow distribution and compared to the S-RELAP5 simulation. The results of the rerun, using the current version of XCOBRA-IIIC, the THINC-IV results, and the S-RELAP5 results are compared in Figure 5.1.26. S-RELAP5 compares with data much better than either XCOBRA-IIIC or THINC-IV.

Figure 5.1.27 compares S-RELAP5 to THINC-IV for the 1500/0 gpm inlet case. Over much of the range, S-RELAP5 fits the data about as well as, or better than, THINC-IV. Near the top of the simulated fuel assemblies S-RELAP5 allows the high flow assembly to retain more flow than does THINC-IV.

Overall, S-RELAP5 does as well as or better than, core flow distribution codes licensed by the NRC for core flow and subchannel analysis of PWR cores (such as XCOBRA-IIIC).

5.1.6 Conclusions

The key results of this benchmark calculation are the following:

- Radial distributions of axial velocities agree well with data from References 20 and 21.
- Flow splits between simulated bundles agree quite well with measured data from Reference 20.

The key results of comparing of S-RELAP5 with flow blockage data are that the two-dimensional model in S-RELAP5 is sufficient to describe flow redistribution in multidimensional problems and that it does as well as thermal-hydraulic design codes used for PWR core analysis (XCOBRA-IIIC and THINC-IV) in predicting the flows.

Table 5.1.1 Flow Boundary Conditions for the Cases Evaluated

Case	Description	Flow to Test Assembly A Lbm/sec	Flow to Test Assembly B Lbm/sec
1	1100/550 gpm	153.00	76.50
1a	1138/512 gpm split	158.28	71.11
2	1500 gpm to one Assembly	208.54	0.0
2a	1281 gpm to one Assembly	178.09	0.0
3	1300 gpm to one Assembly	180.74	0.0

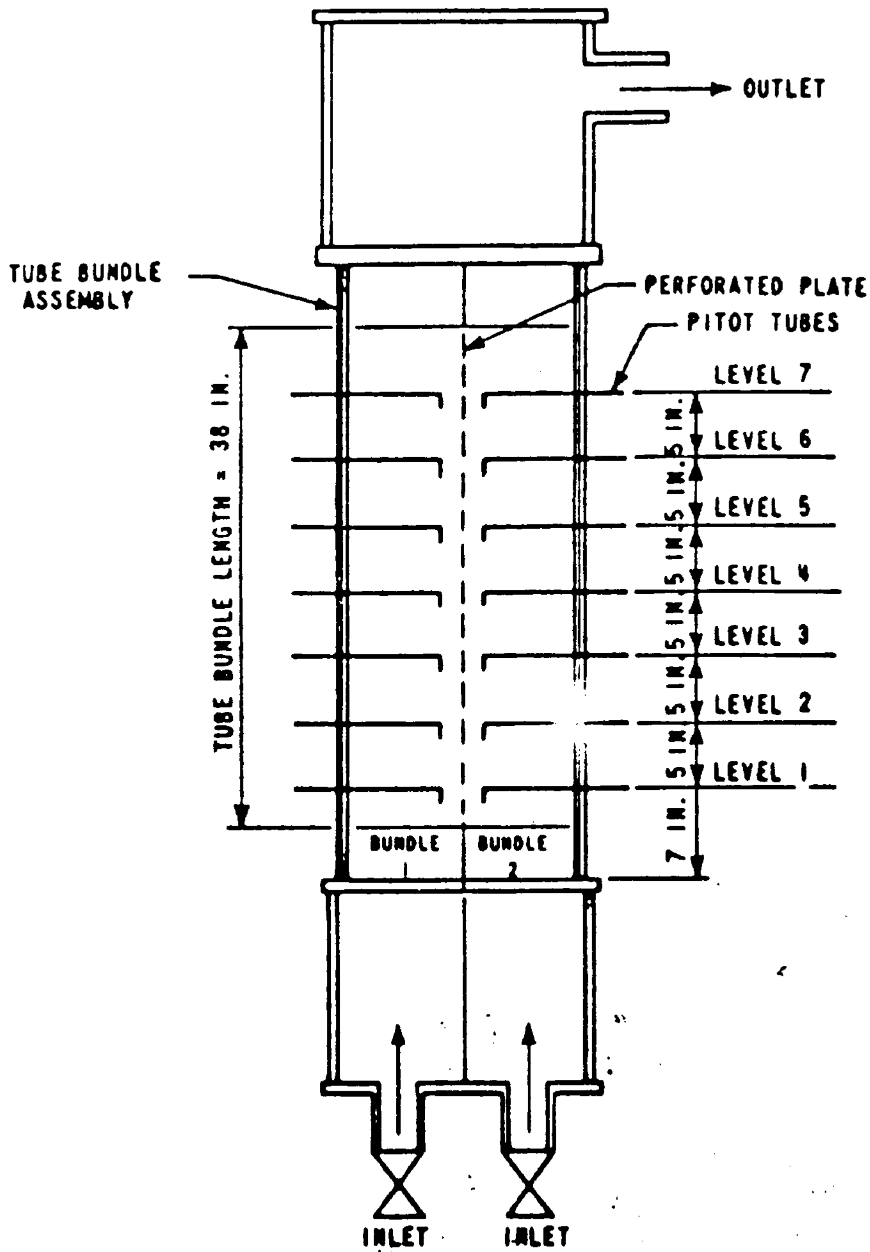


Figure 5.1.1 Test Rig for Flow Blockage Tests Showing Location of Perforated Plate

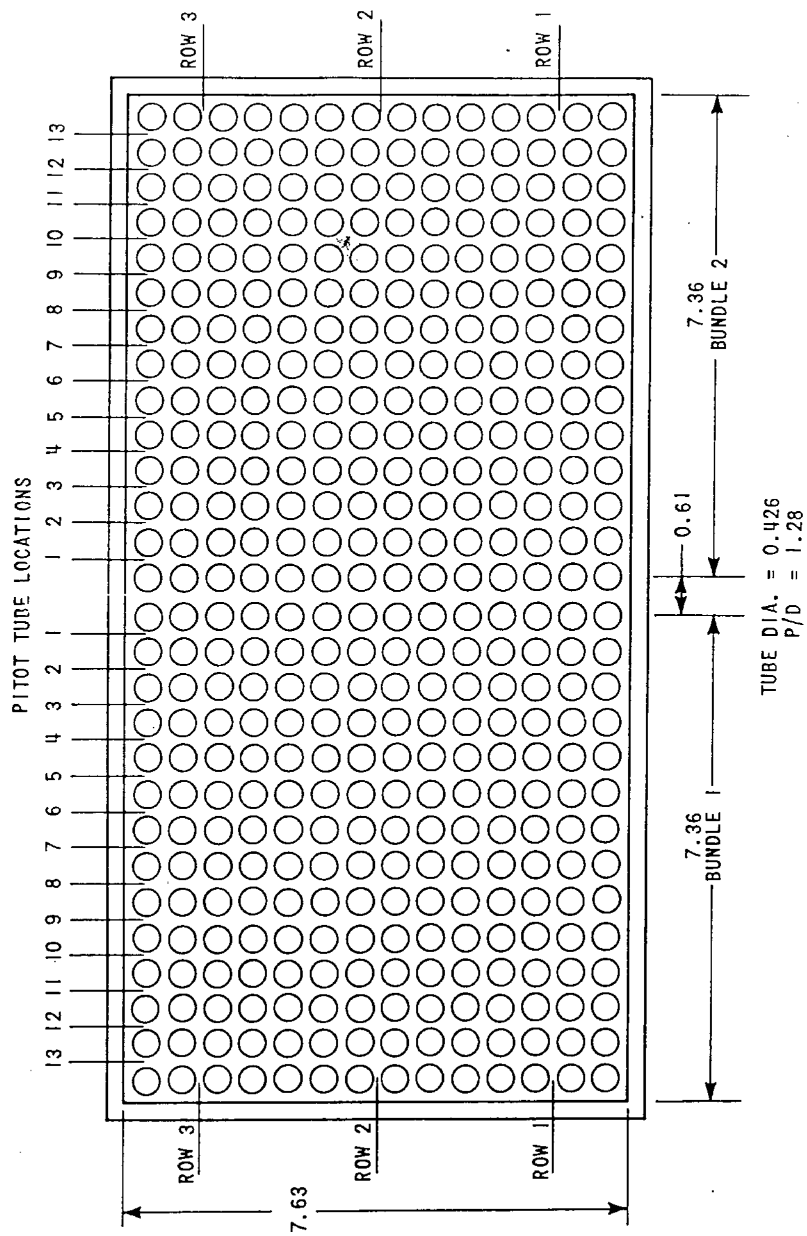


Figure 5.1.2 Cross Sectional View of Test Assemblies Without Perforated Plate Between Test Assemblies

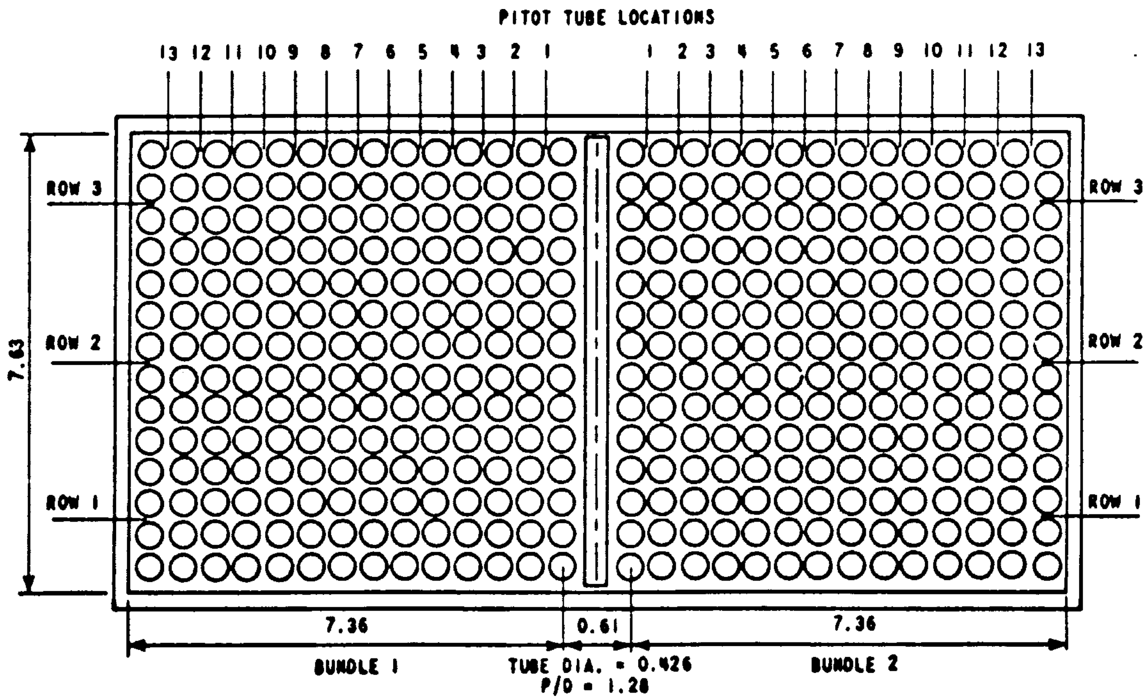


Figure 5.1.3 Cross Sectional View of Test Assemblies with Perforated Plate Between Test Assemblies

Figure 5.1.4 Nodalization Diagram for S-RELAP5 Modeling of Westinghouse Flow Blockage Tests

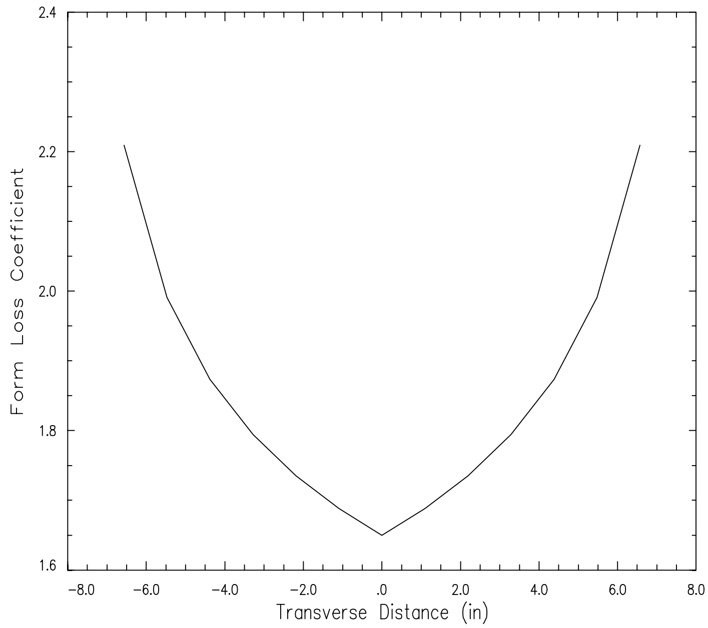


Figure 5.1.5 Form Loss for Lateral Flow (Typical)

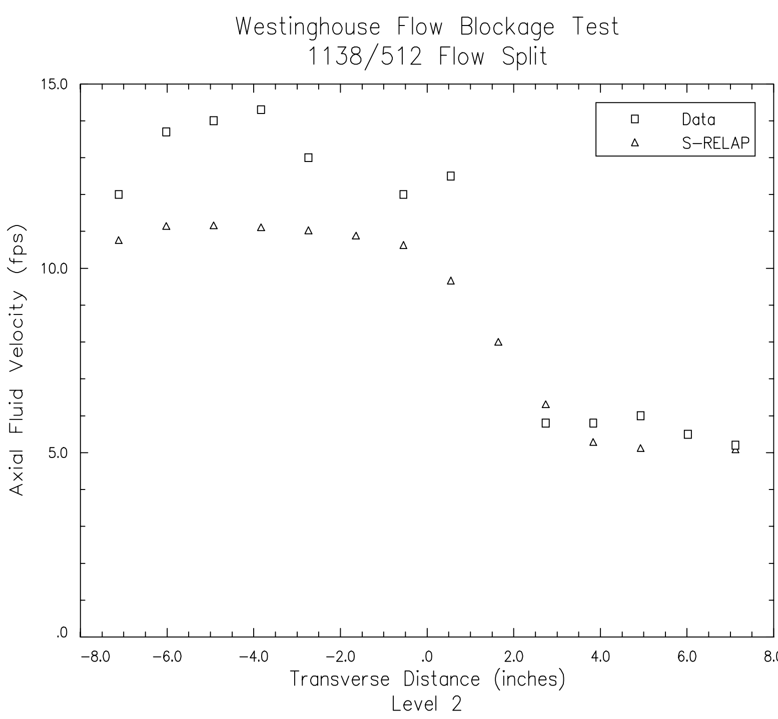


Figure 5.1.6 Axial Velocities at 7.5-Inches for Asymmetric Flow (1138/512)

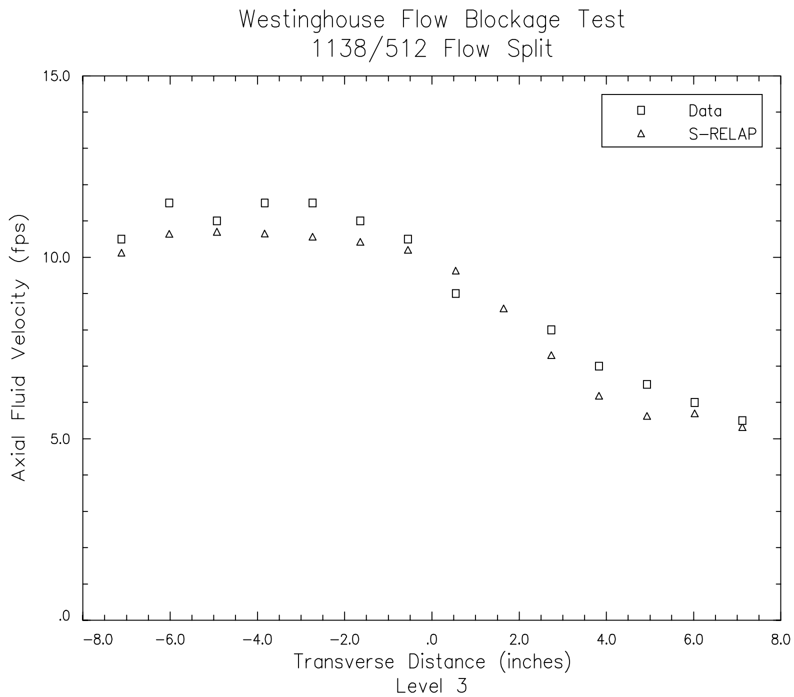


Figure 5.1.7 Axial Velocities at 12.5-Inches for Asymmetric Flow (1138/512)

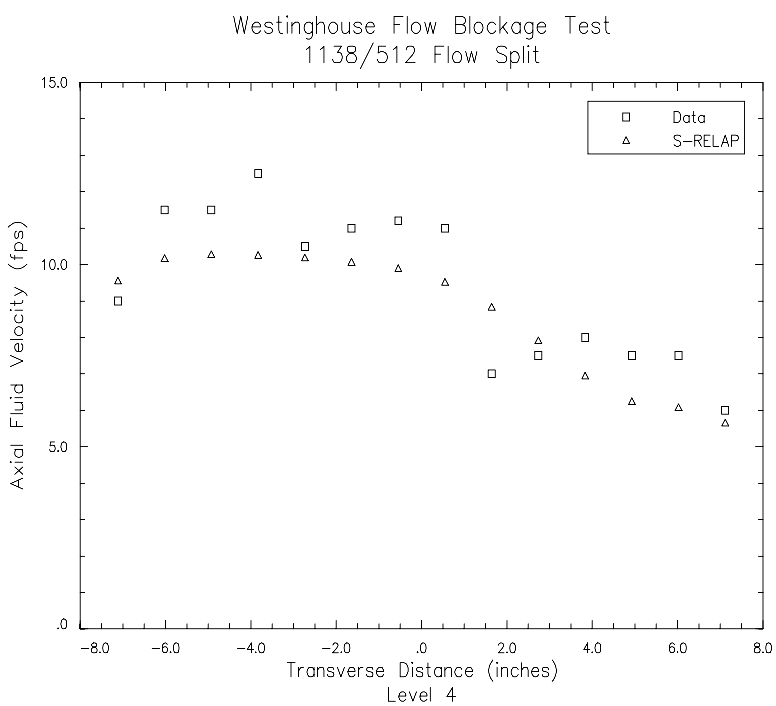


Figure 5.1.8 Axial Velocities at 17.5-Inches for Asymmetric Flow (1138/512)

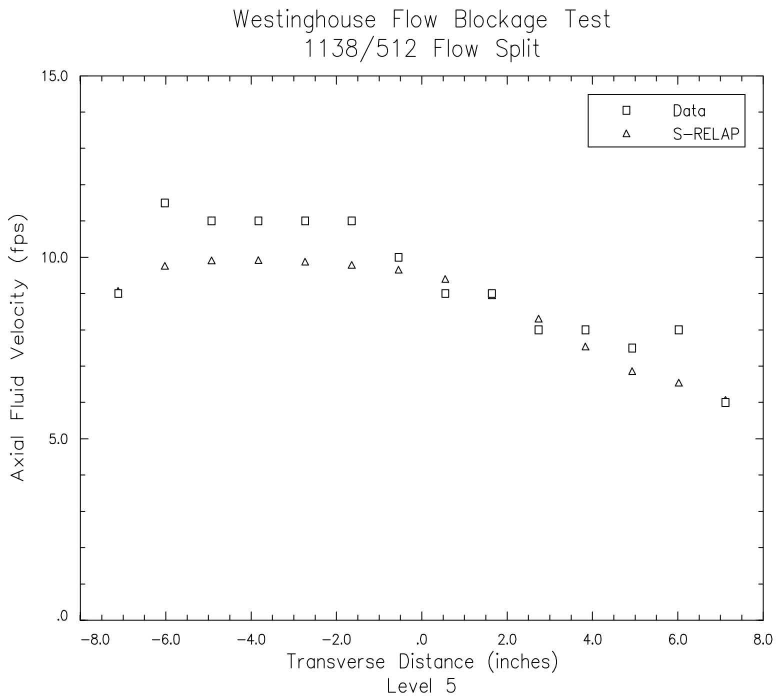


Figure 5.1.9 Axial Velocities at 22.5-Inches for Asymmetric Flow (1138/512).

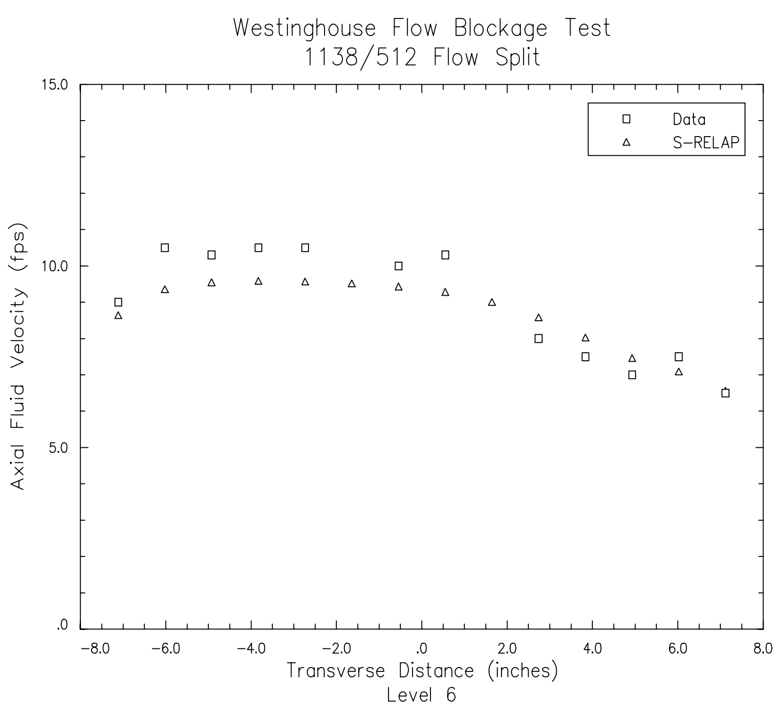


Figure 5.1.10 Axial Velocities at 27.5-Inches for Asymmetric Flow (1138/512).

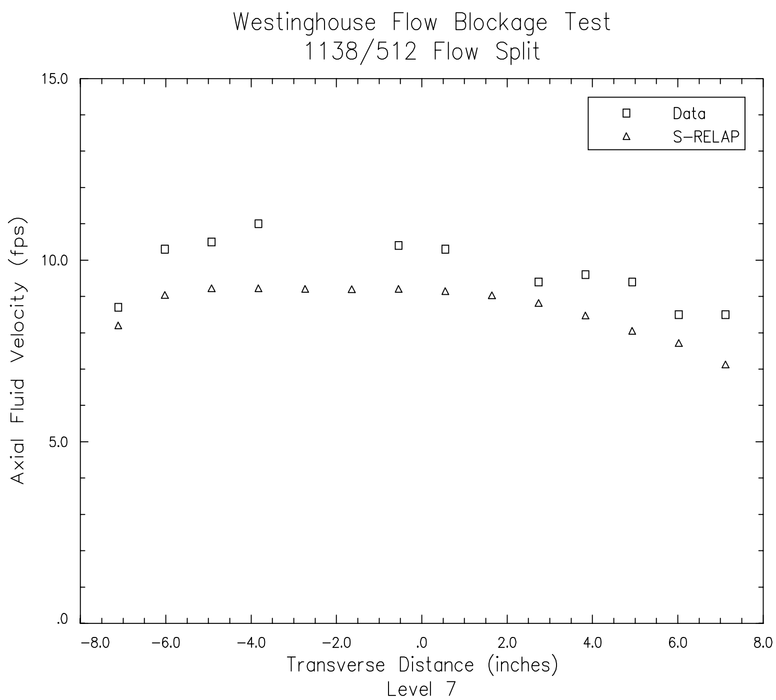


Figure 5.1.11 Axial Velocities at 32.5-Inches for Asymmetric Flow (1138/512)

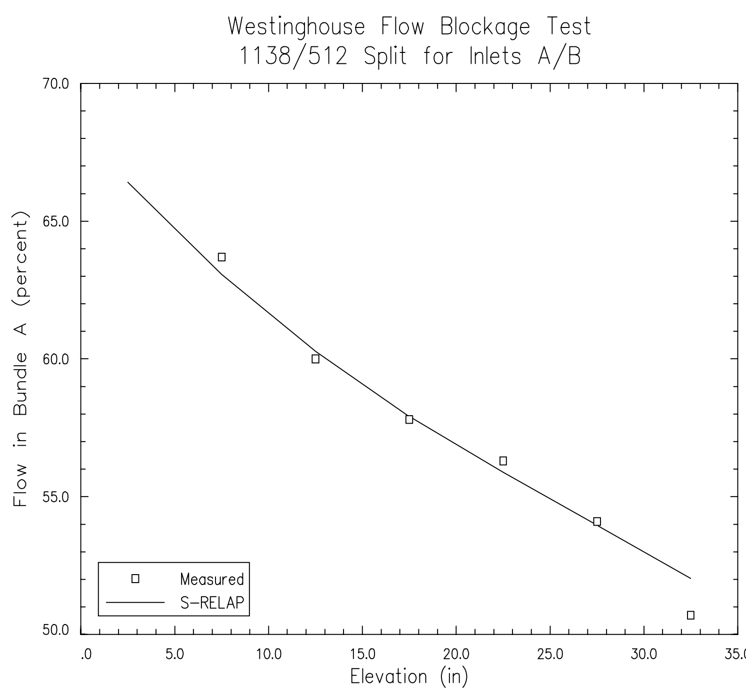


Figure 5.1.12 Axial Flow Fractions for Asymmetric Flow (1138/512)

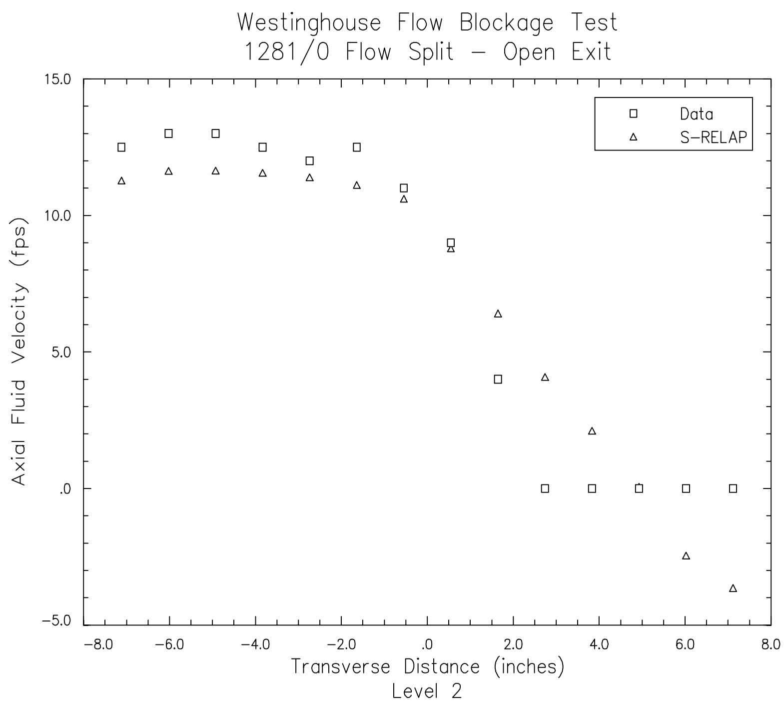


Figure 5.1.13 Axial Velocities at 7.5-Inches for Asymmetric Flow (1281/0)

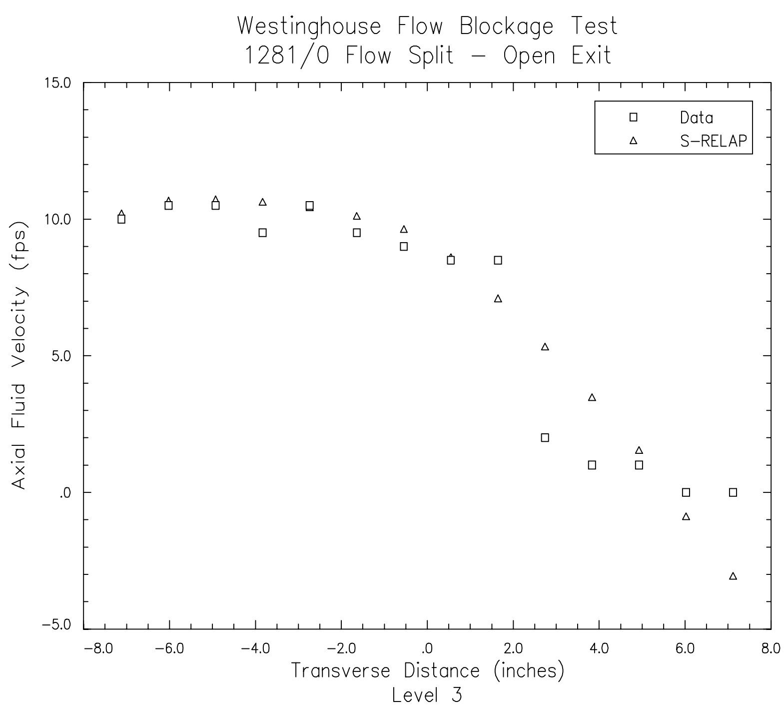


Figure 5.1.14 Axial Velocities at 12.5-Inches for Asymmetric Flow (1281/0).

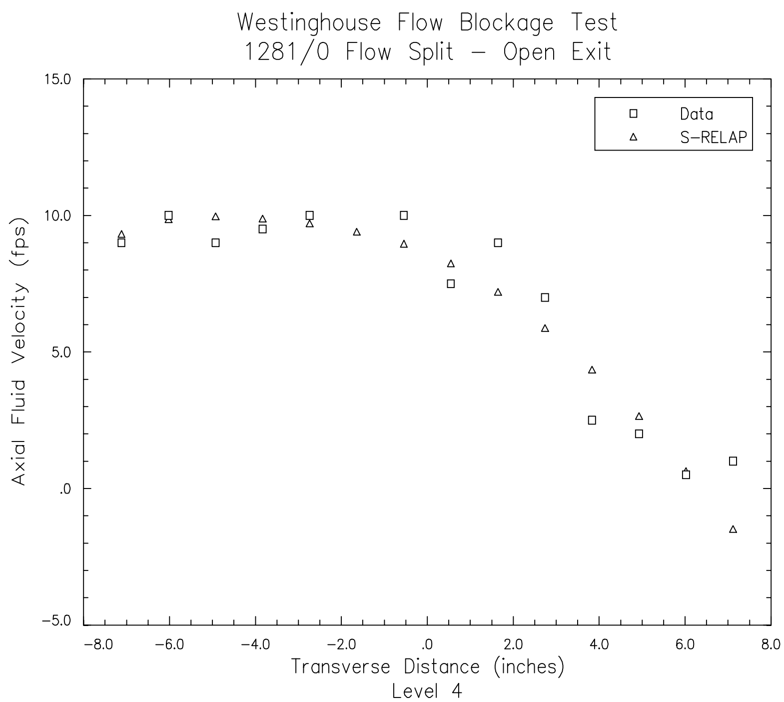


Figure 5.1.15 Axial Velocities at 17.5-Inches for Asymmetric Flow (1281/0).

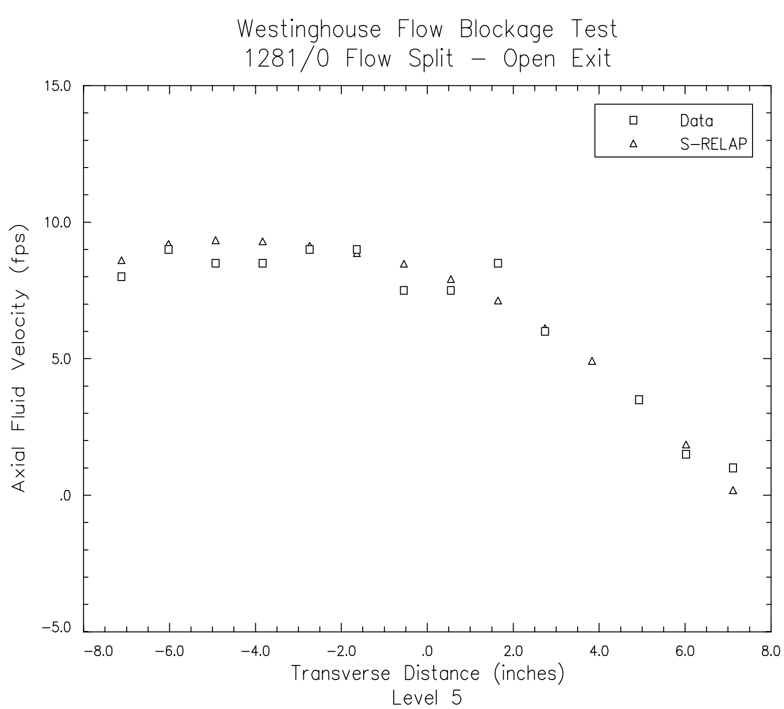


Figure 5.1.16 Axial Velocities at 22.5-Inches for Asymmetric Flow (1281/0)

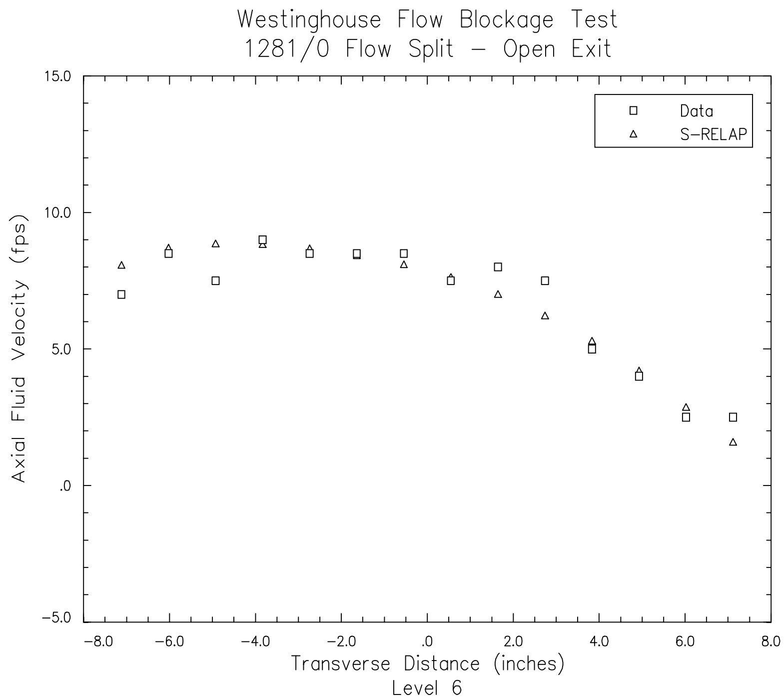


Figure 5.1.17 Axial Velocities at 27.5-Inches for Asymmetric Flow (1281/0)

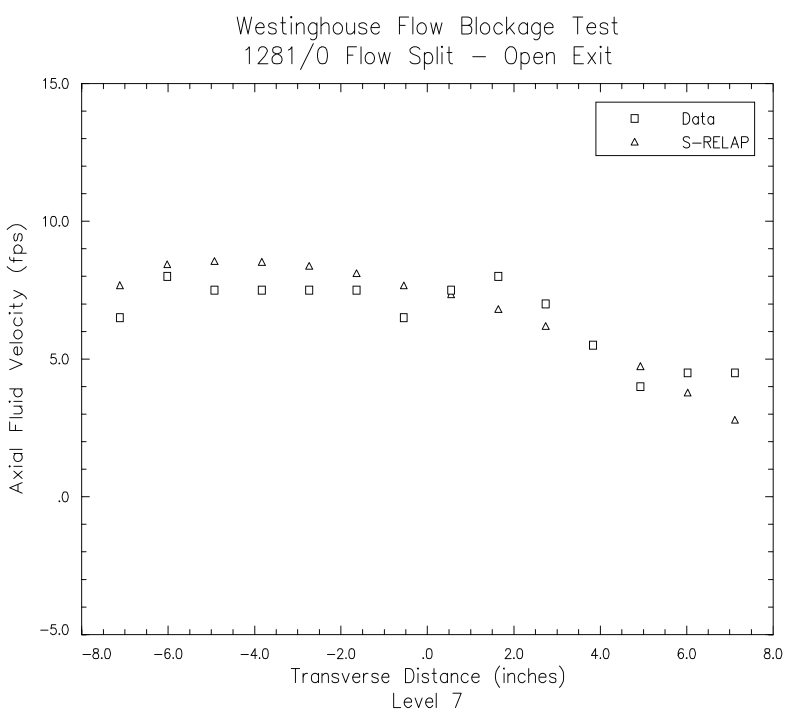


Figure 5.1.18 Axial Velocities at 32.5-Inches for Asymmetric Flow (1281/0)

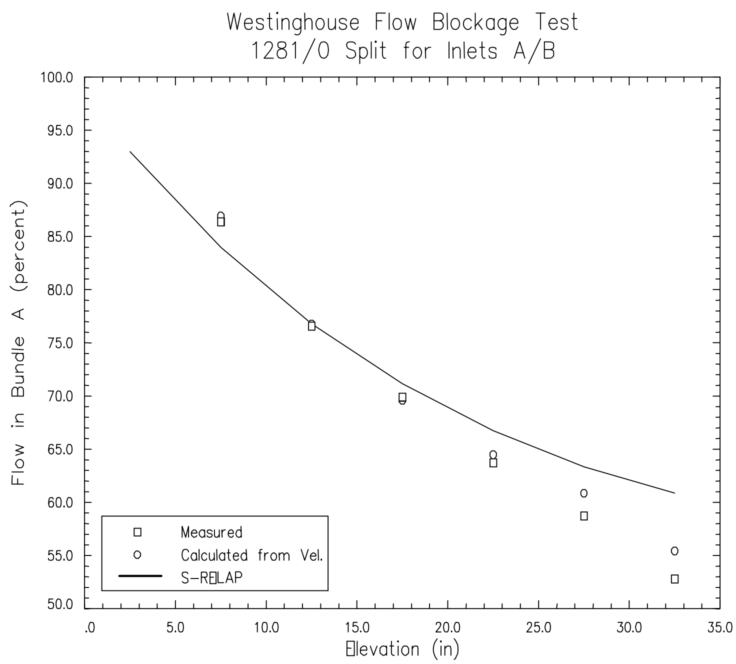


Figure 5.1.19 Axial Flow Fractions for Asymmetric Flow–Blocked Inlet Comparison of S-RELAP5 to Flow Data and Flow Fractions Based on Velocities

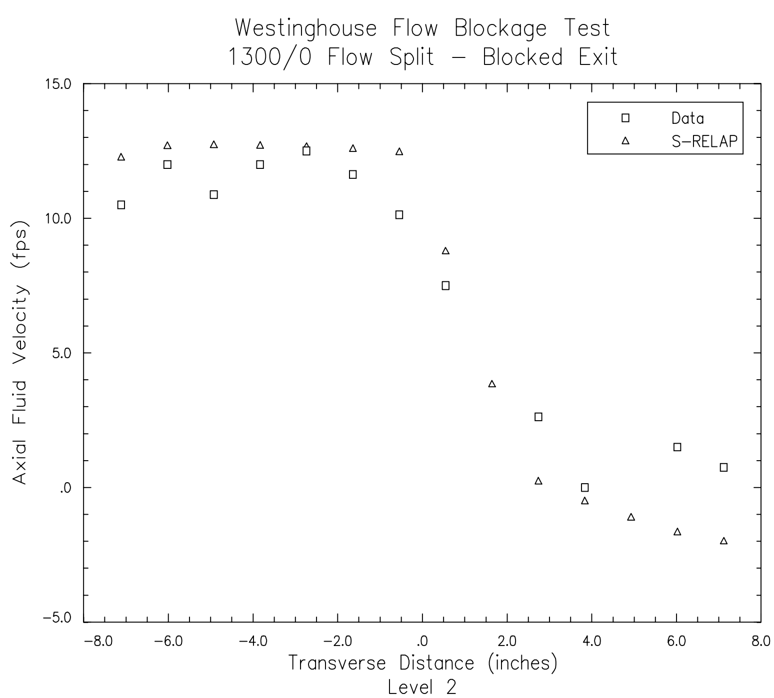


Figure 5.1.20 Axial Velocities at 7.5-Inches for Asymmetric Flow (1300/0) – Blocked Exit for Assembly B

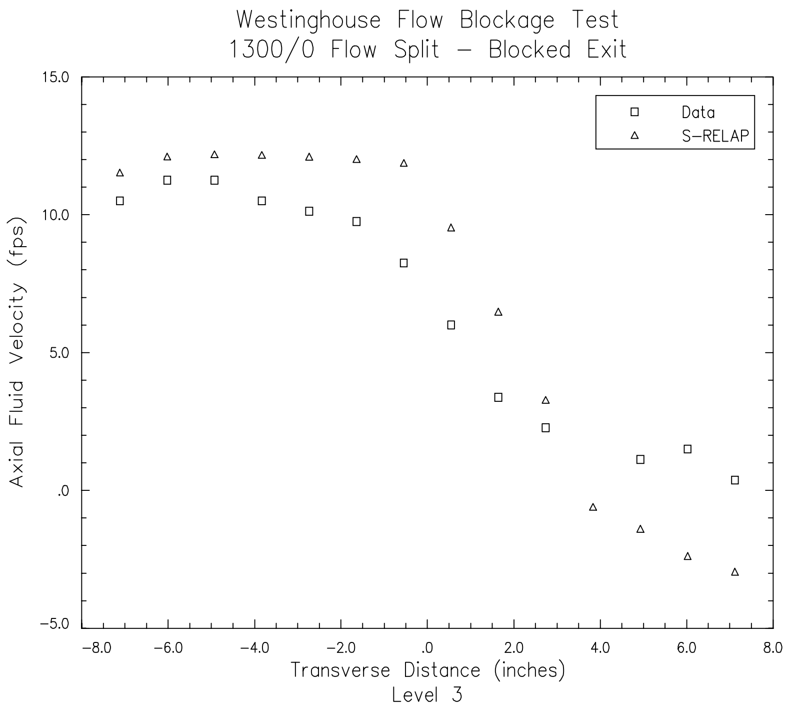


Figure 5.1.21 Axial Velocities at 12.5-Inches for Asymmetric Flow (1300/0) – Blocked Exit for Assembly B

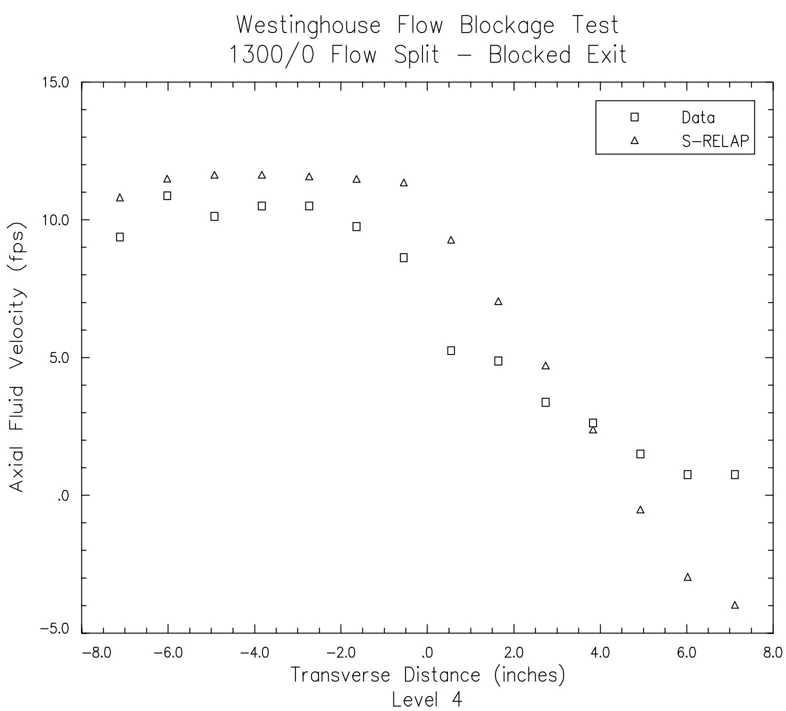


Figure 5.1.22 Axial Velocities at 17.5-Inches for Asymmetric Flow (1300/0) – Blocked Exit for Assembly B

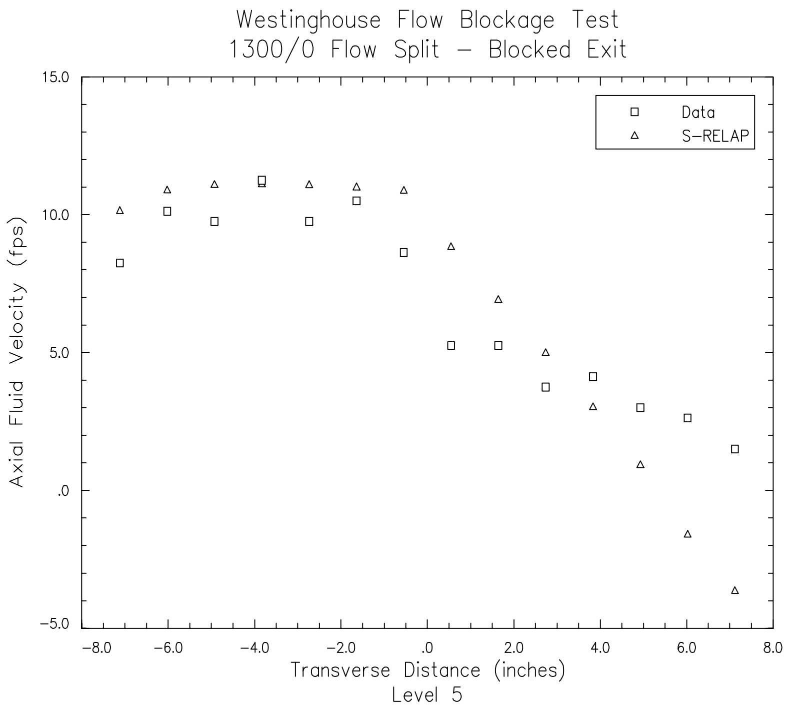


Figure 5.1.23 Axial Velocities at 22.5-Inches for Asymmetric Flow (1300/0) – Blocked Exit for Assembly B

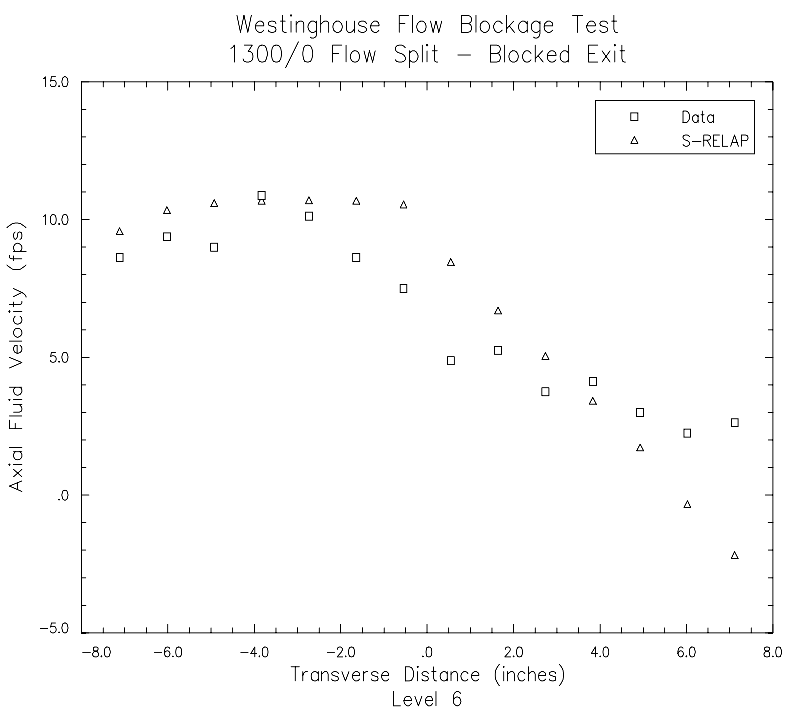


Figure 5.1.24 Axial Velocities at 27.5-Inches for Asymmetric Flow (1300/0) – Blocked Exit for Assembly B

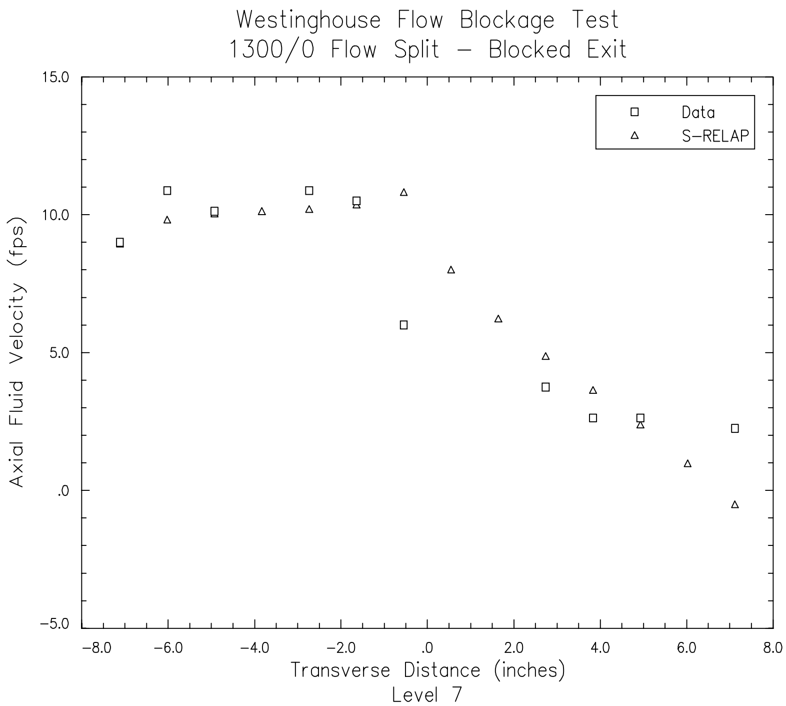


Figure 5.1.25 Axial Velocities at 32.5-Inches for Asymmetric Flow (1300/0) – Blocked Exit for Assembly B

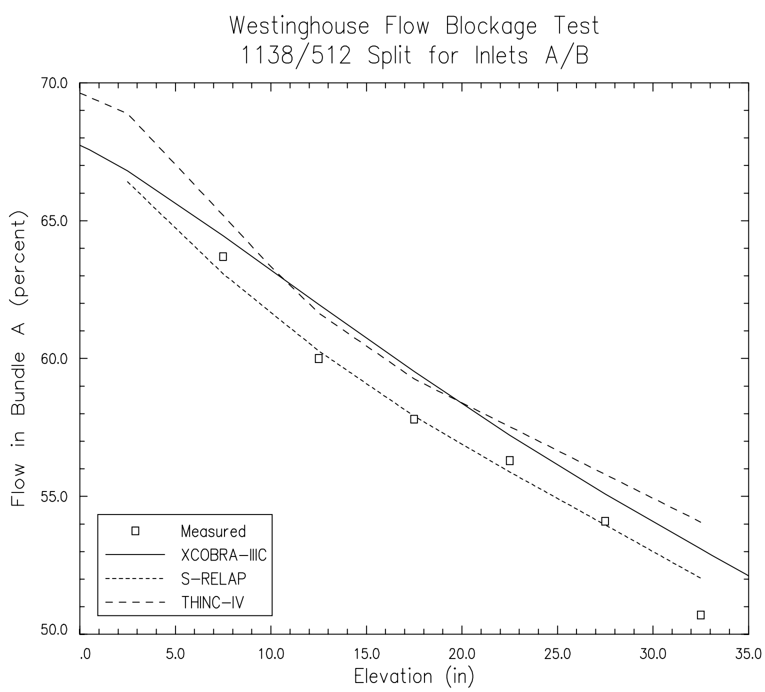


Figure 5.1.26 Comparison of S-RELAP5 with THINC-IV for Asymmetric Flow (1138/512)

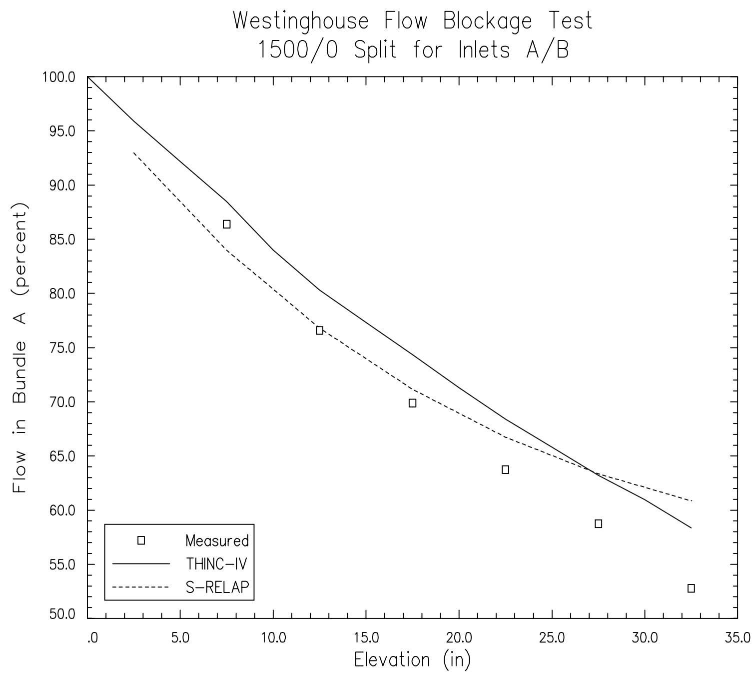


Figure 5.1.27 Comparison of S-RELAP5 with THINC-IV for Asymmetric Flow (1500/0)

5.2 *Semiscale Test S-UT-8*

The S-UT series of small break tests was performed in the Semiscale Mod-2A test facility at INEEL. The base series of tests was designed to investigate the effect of ECCS on a SBLOCA in a PWR with an upper-head injection system. Test S-UT-8 was added to the series as a variation of the baseline test, S-UT-6. The S-UT-8 test was characterized by deep core uncovering due to increased amounts of liquid held up in the upflow side of the steam generators, compared to test S-UT-6. The primary differences between the tests were that S-UT-8 had significantly less bypass flow from the downcomer to the upper plenum (1.5% for S-UT-8, 4% for S-UT-6). The decreased bypass flow contributed to the deep core uncovering by increasing the steam flow to the steam generators thereby increasing condensation potential, and to delay the downflow side draining of liquid from the steam generator. The S-UT-8 test was simulated with S-RELAP5 to demonstrate that S-RELAP5 could reproduce the liquid hold-up in the upflow side of the steam generator and cause a subsequent deep core uncovering.

5.2.1 <u>Test Facility Description</u>

The Mod-2A system was scaled to have a core power and system fluid volume 1/1700 of a four-loop PWR. The intact loop had three times the fluid volume and loop mass flow of the broken loop and represented three of the four operational loops. ECCS included a high-pressure injection system, passive accumulators, and a low-pressure injection system. The test facility is illustrated in Figure 5.2.1.

The flow passing from the downcomer to the upper plenum by way of the upper head was reduced to about 1.5% in S-UT-8, compared to 4.0% in S-UT-6. Reference 23 showed that prolonged flooding in the ascending tubes of the steam generators caused the long, deep core uncovery seen in S-UT-8. Table 5.2.1 shows the sequence of events for the S-UT-8 test.

Table 5.2.1 Sequence of Events for Semiscale Test S-UT-8

Event	Test (sec)	S-RELAP5 (sec)
Break initiation	0.	0.
Steam flow valves closed	unknown	9.2
SG feedwater flow stopped		
Intact loop	unknown	9.2
Broken loop	unknown	9.2
HHSI began (trip 508)	35.	33.
Core heatup began	168	142
Downflow side of intact loop SG tubes drained	170	148
Upflow side of intact loop SG tubes drained	225	200
Core temperatures recover	240	~270

5.2.2 S-RELAP5 Model Description

The S-RELAP5 model, shown in Figure 5.2.2, was derived from a model originally developed at INEEL and was used by SPC in 1986 for ANF-RELAP simulations of test S-UT-8 (Reference 1). The model was modified for this analysis to incorporate model changes, where applicable, from using the recently developed methodology presented in this report.

[

]

5.2.3 Boundary Conditions

Test S-UT-8 was initiated by opening the break valves. Core power was tripped on low pressurizer level and followed a programmed decline simulating decay heat in an operating reactor. The feedwater and steam line valves were closed coincident with the core power trip. Pump trip and coastdown occurred shortly thereafter. ECCS actuation occurred on low primary system pressure; injection was only to the intact loop. Reference 23 contains a comprehensive discussion of S-UT-8.

5.2.4 Comparison to Data

The event sequences for the test and the S-RELAP5 simulation are compared in Table 5.2.1, and the comparisons to measured data are summarized in Table 5.2.2. In some cases, the test reports do not include certain event times. These are marked “unknown” in the table. Overall, the event times show general agreement.

Figure 5.2.3 compares the calculated and measured primary system pressure over the first 300 seconds of the test. The primary system pressure calculated by S-RELAP5 is slightly above the measured pressure until about 270 seconds. This is because of the over-predicted steam generator pressures, shown in Figure 5.2.4. The steam generator pressures were over-predicted due to valve closure rate and feedwater cessation uncertainties from the S-RELAP5 calculation. The over-predicted steam generator pressure contributed to event timing discrepancies, but did not invalidate the comparisons to measured data.

Figure 5.2.5 compares the experimental and calculated amounts of mass expelled out the break. The agreement between the two is excellent for the first 75 seconds of the transient. After that the calculated amount of mass expelled is slightly lower than the measured amount due to the break uncovering earlier in transient than the data indicates. [

]

Figure 5.2.6 shows the collapsed level in the ascending tubes for the intact steam generator and Figure 5.2.7 shows the collapsed level in the descending side of the steam generator. S-RELAP5 agrees very good with the ascending side data, and fair with the descending side data. The data show increasing levels from 50 to 100 seconds, while only the ascending side from the S-RELAP5 calculation shows the increase. Both comparisons show S-RELAP5 leading the data, which is consistent with the early break uncovering time calculated by S-RELAP5. These figures show that S-RELAP5 adequately simulates the holdup of liquid in the steam generator tubes.

Figure 5.2.8 shows the collapsed level in the core. The drop in level calculated by S-RELAP5 at 100 seconds is caused by the early transition from single to two phase break flow. The early break flow transition and the lack of liquid hold-up in the down-flow side of the steam generator also causes an earlier core dryout in the simulation. The heatups for both the calculation and the test begins when the collapsed levels fall below 180 cm. The calculated level did not drop as far as the measured level and began recovering sooner. However the measured level reached 180 cm on recovery before 250 seconds and the simulated level did not reach 180 cm until about 270 seconds. Thus, the heat-up period for the simulation was much longer.

The effects of the earlier and longer dryout are shown in Figure 5.2.9, the cladding temperature at the 6-foot (1.83 m) elevation. The S-RELAP5 temperatures shown for comparison are calculated from nodes spanning the 6 foot elevation and are taken from mesh points within the structure that approximate the thermal-couple location. The slightly higher calculated temperature between 50 and 150 seconds is due to the slightly higher primary pressure and corresponding saturation temperature. The measured dryout at this elevation occurred at 168 seconds. In the simulation, the S-RELAP5 dryout occurred approximately 25 seconds earlier. The peak temperature from S-RELAP5 is greater than the experimental temperature.

5.2.5 Conclusions

Table 5.2.2 summarizes the results obtained in this analysis. PCTs have been rounded to the next highest whole number.

Table 5.2.2 Summary of Calculated PCTs.

Parameter	Time, s	PCT, K (°F)
Measured PCT	226	682 (768)
S-RELAP5	254	698 (797)

S-RELAP5 approximated the early hydraulic behavior seen in the experiment; a deep core uncovering due to holdup of liquid in the up-flow side of the steam generator and CCFL at the core outlet. The calculated core mid-plane temperature response agreed well with the data. In the core mid-plane, S-RELAP5 predicted CHF to occur sooner than it actually occurred and predicted PCTs which are close to, yet above, the data. These results indicate that S-RELAP5 can simulate the core heat-up prior to loop seal clearing in SBLOCA events.

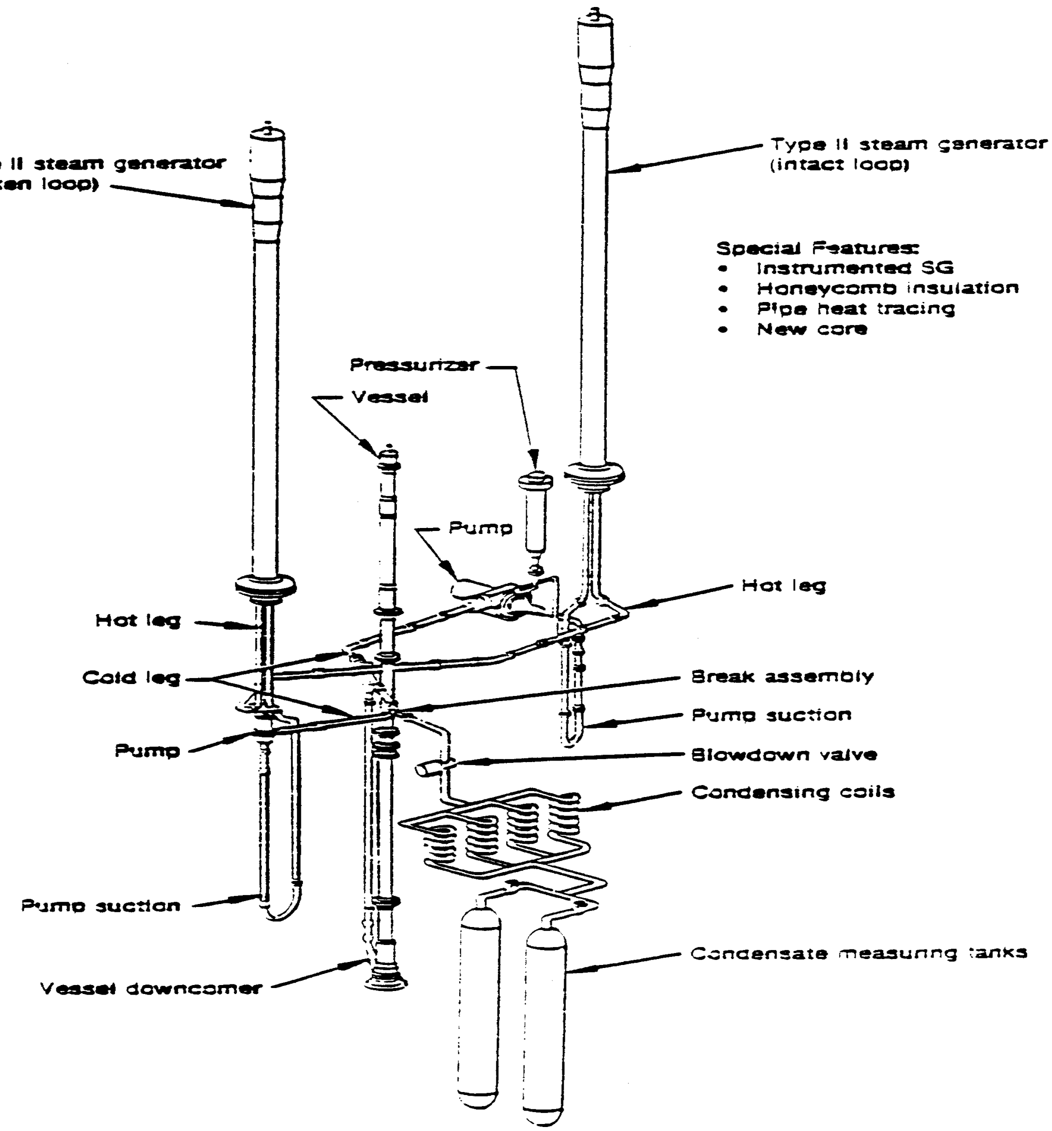


Figure 5.2.1 Isometric of the Semiscale Mod-2A Facility

Figure 5.2.2 S-RELAP5 Nodalization for S-UT-8 Simulations

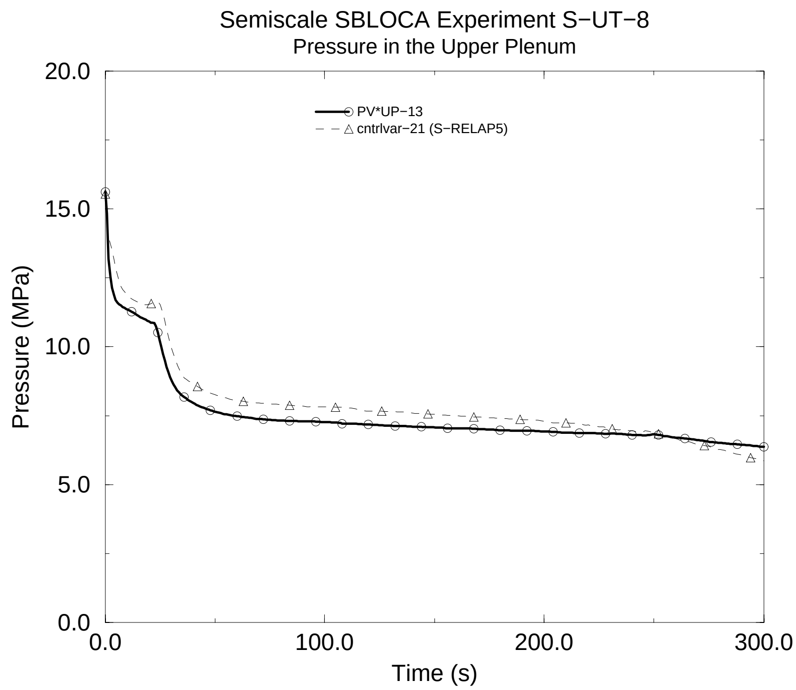


Figure 5.2.3 Primary System Pressure (Upper Plenum)

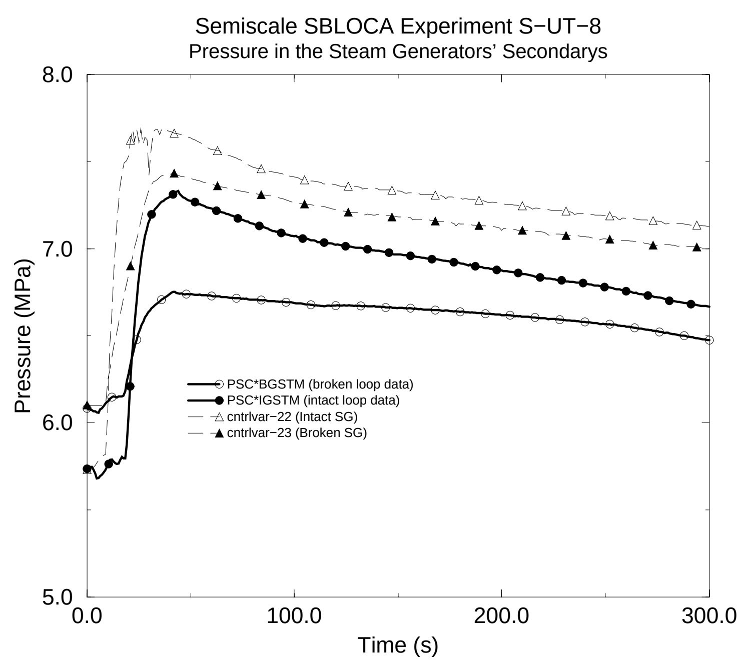


Figure 5.2.4 Secondary Side Pressures

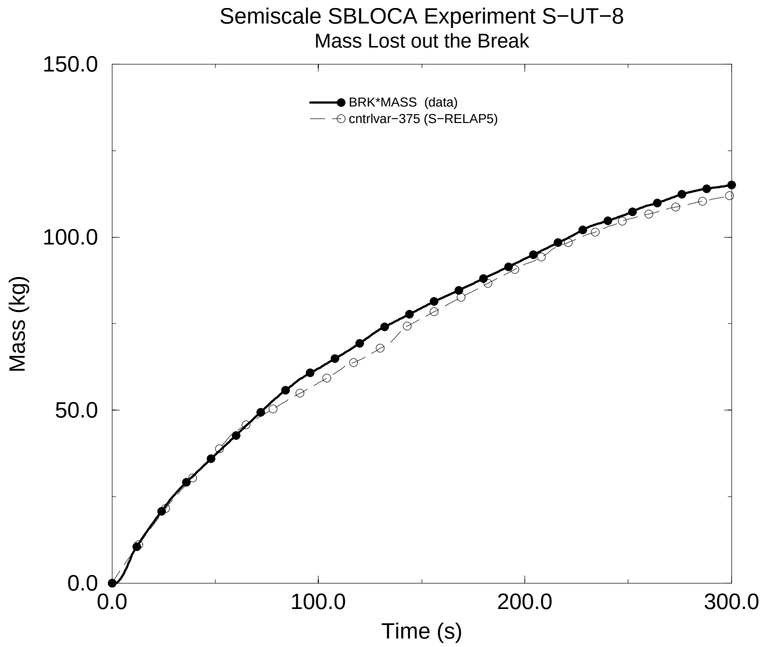


Figure 5.2.5 Integrated Break Flow

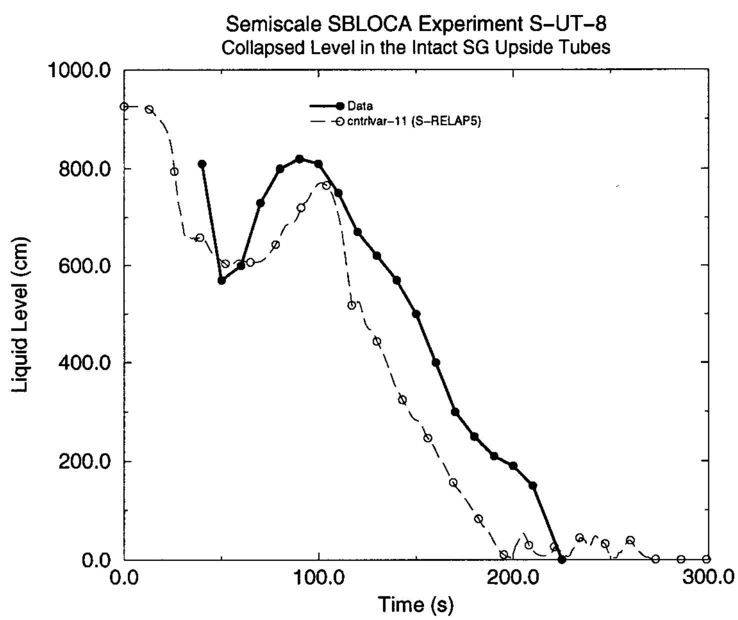


Figure 5.2.6 Collapsed Level in the Intact SG Upflow Tubes

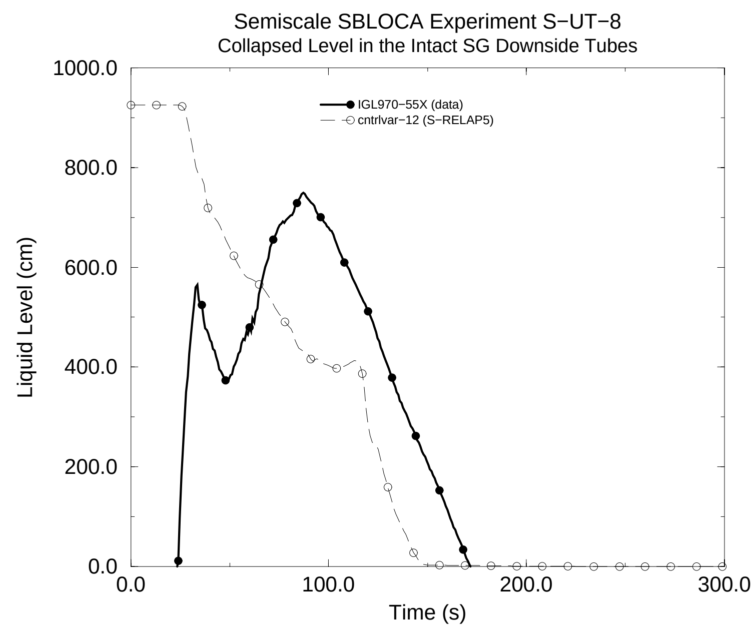


Figure 5.2.7 Collapsed Level in the Intact SG Downflow Tubes

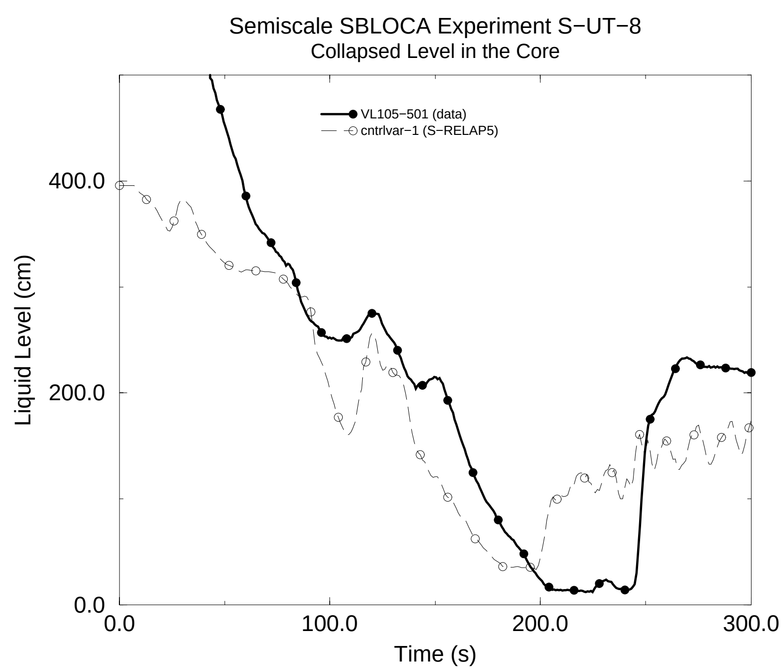


Figure 5.2.8 Collapsed Level in the Core

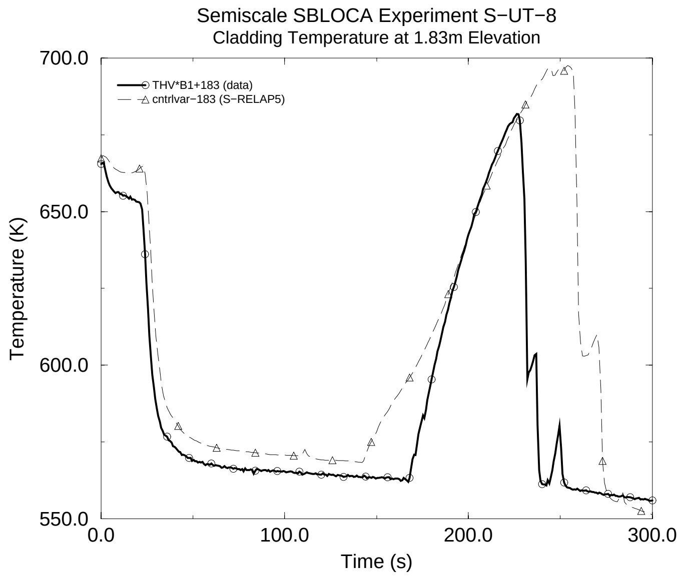


Figure 5.2.9 Core Mid-Plane Cladding Temperature

5.3 ***LOFT LP-SB-03***

The LP-SB-3 test was the last test studying small-break phenomena at the loss of fluid test (LOFT) facility. One objective of this test was to investigate core heat transfer when core uncovery occurs during relatively slow boil-off conditions (Reference 24). This section briefly describes the test facility, the test conditions for the LP-SB-3 test, and the S-RELAP5 simulation model, and compares calculated results from S-RELAP5, previous ANF-RELAP calculations, and measured data.

5.3.1 Test Facility Description

The LOFT facility was designed to simulate the major components and system responses of a full-scale PWR during a LOCA. The experimental facility includes five major systems that are instrumented so system variables can be measured and recorded during an experiment. The systems include the reactor vessel, the intact loop, the broken loop, the blowdown suppression system, and the ECCS. The system of interest for this application, the reactor vessel, is shown in Figure 5.3.1. Reference 25 describes the LOFT system in more detail.

5.3.2 S-RELAP5 Model Description

The period of interest for a boil-off investigation is approximately 1500 seconds starting at 3500 seconds into the transient. Therefore, an abbreviated system model was developed to simulate the core boil-off period exclusively. [

]

Heat structures representing the hot rod, hot assembly, and outer core region were initialized to conditions equal to the experimental values at 3500 seconds. Also, the hydrodynamic components were set to the experimental condition at 3500 seconds. A steady-state calculation was made to establish two-phase conditions in the core region similar to those found in the experiment. A transient calculation was made for 1500 transient seconds and the calculated results were shifted approximately 3500 seconds to the time frame of core boil-off by matching the measured and calculated dryout times.

5.3.3 Event Description

The description of the test is given in Reference 26. The experiment was initiated by opening the break valve in the intact-loop cold-leg break line. The reactor scrammed at a primary system pressure of 2057.6 psia at 9.2 seconds. The steam generator control system responded to the reactor scram by isolating the feedwater flow to the steam generator and the steam flow out of the steam generator. The main feedwater pump power was terminated at 9.4 seconds and the main feedwater valve was isolated at 10.8 seconds. The main steam control valve (MSCV) began closing at 9.5 seconds and was fully closed at 21 seconds. The secondary system pressure increased sharply after reactor scram because of the feedwater shutoff and MSCV closure. The first cycle of MSCV occurred at 87.5 seconds to keep the secondary side pressure between 1032 and 932 psia. The MSCV cycled four times, with the last cycle occurring at 1030 seconds. Fluid saturation conditions were reached in the piping to the break at about 100 seconds.

Table 5.3.1 Event Sequence

Event	Test (sec)
Break initiation, intact-loop cold-leg break line	0.
Reactor scram	9.2
SG main feedwater pump trip	9.4
SG main feedwater valve closed	10.8
Pump tripped	1600
Break uncovered	1612
Core heatup began	3800
Break isolated	4742
Initiation of ‘feed and bleed’	5415
Experiment end time	6845

At 875 seconds, the rate of pressure increase slowed abruptly. The primary coolant pumps tripped at 1600 seconds. The reduction of the pump head caused an uncovery of the break at 1612 seconds.

As the liquid level fell in the core, the upper part of the core started to heat up at 3800 seconds. The break was isolated at 4742 seconds, when the highest indicated cladding temperature reached 1000 °F.

The cladding temperature continued to rise until the highest indicated value reached 1300 °F at 5415 seconds. A secondary system feed-and-bleed operation was initiated at that time by fully opening the MSCV bypass valve and operating the main feedwater pump. This action caused a very rapid cool down and depressurization of the secondary system while the fuel clad temperature continued to increase, reaching the maximum value of 1318 °F at 5422 seconds. The primary system started depressurizing and cooling down at that time. The primary system pressure reached the accumulator setpoint at 5558 seconds, at which time the accumulator injection began.

At 6785 seconds, the pressure fell low enough that the low-pressure injection pump started injecting, and the experiment was terminated at 6845 seconds.

5.3.4 Comparison to Data

The results from this calculation are shown in Figure 5.3.3 through Figure 5.3.6. For comparison, results calculated using ANF-RELAP also are shown. The over-predicted temperature at the 28 inch elevation shown in Figure 5.3.5 is due to a cooling mechanism in the experiment not modeled in the code calculation. The overall comparison between S-RELAP5 and measured data is acceptable under the conditions assumed for this calculation.

[

]

System mass responses also were compared for the code calculations. Both cases started with approximately the same total mass. At the end of the transient calculations, the PCS contained about 4% more mass in the S-RELAP5 run than in the ANF-RELAP run. However, throughout the transient, S-RELAP5 has a slightly higher mass flow out of the core and higher flow into the downcomer compared to ANF-RELAP. Also, the mass flow exiting the system was slightly lower from S-RELAP5 compared to

ANF-RELAP. Overall, these differences are small and considered insignificant, however they do cause slight differences in direct comparisons.

5.3.5 Conclusions

The results of comparisons between S-RELAP5 and ANF-RELAP showed significant differences (more than 50 °F) between the calculated results at the 28-inch elevation. The temperature comparisons at the 49-inch elevation showed insignificant differences. The mixture level plots show that the boil-off rates calculated from both codes are very similar, but small differences exist at specific locations. Overall, the comparisons show little difference between ANF-RELAP and S-RELAP5 as applied to the LOFT LP-SB-3 test. The comparisons between measured data and S-RELAP5 show the code is capable of calculating the expected boil-off and fuel heatup during the SBLOCA event in a conservative manner.

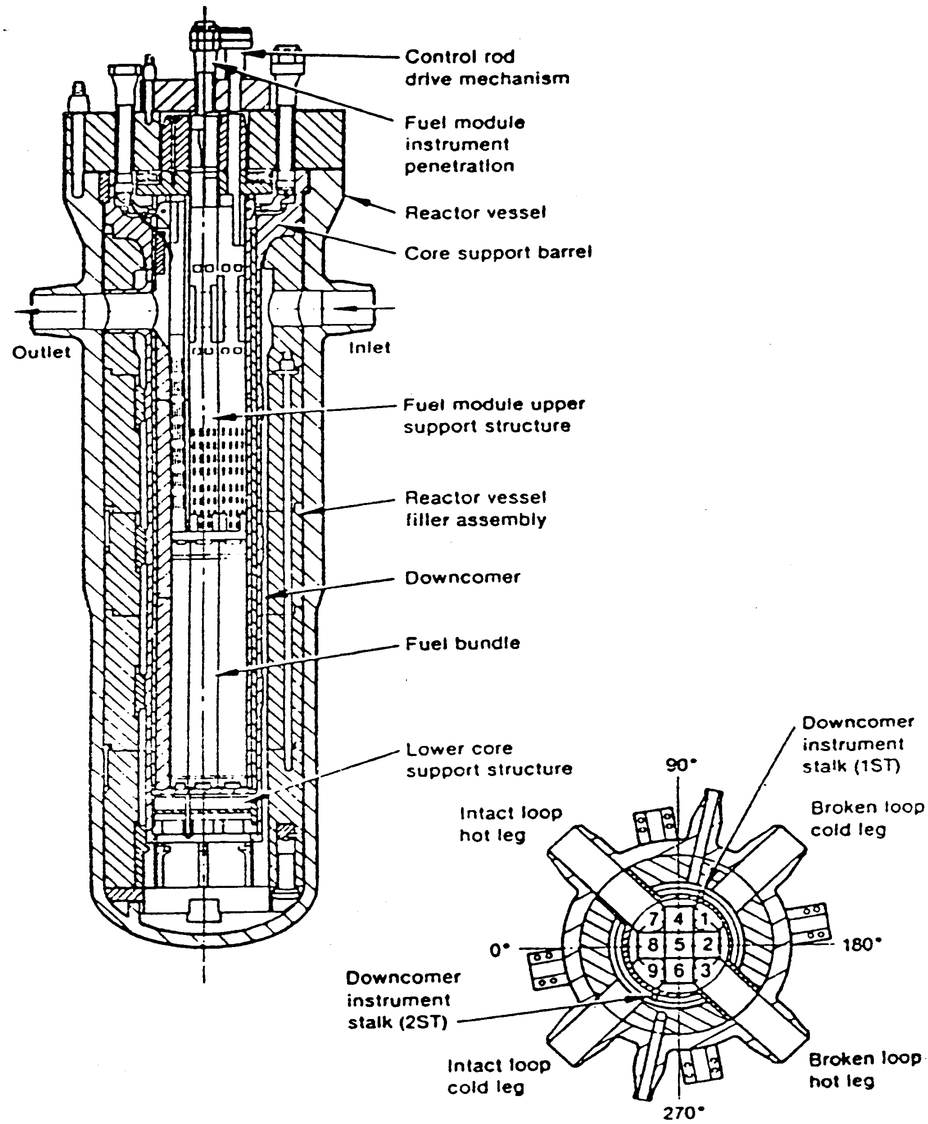


Figure 5.3.1 LOFT Reactor Vessel Assembly.

Figure 5.3.2 Primary System Nodalization

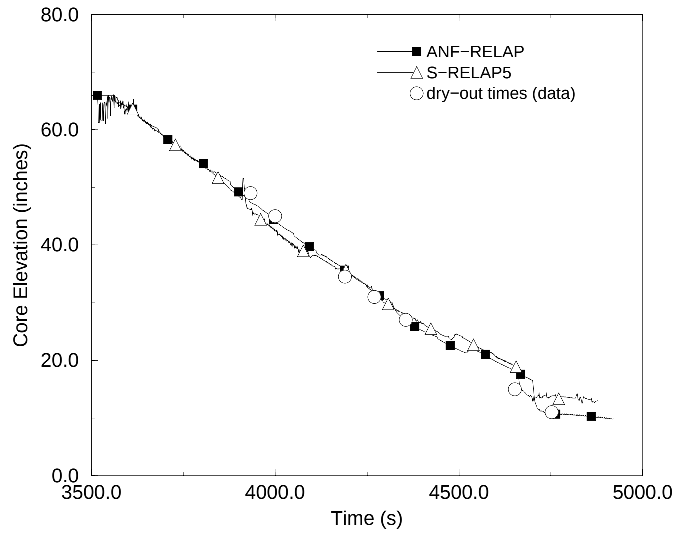


Figure 5.3.3 S-RELAP5 Mixture Level Using Two-Dimensional Core Model Compared to LOFT Data and ANF-RELAP Calculation

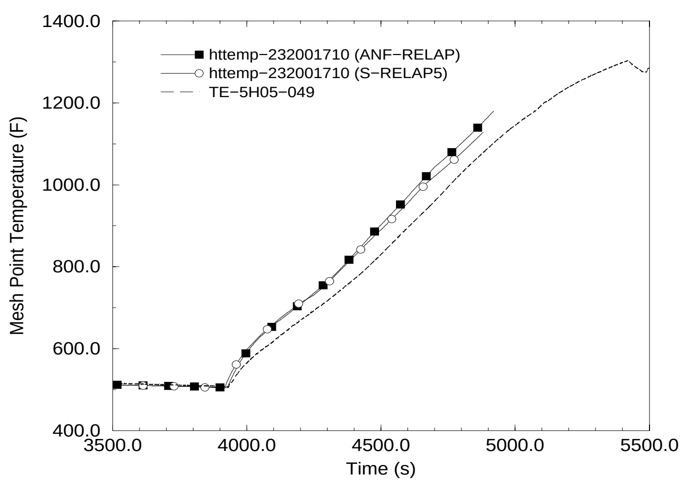


Figure 5.3.4 S-RELAP5 Clad Temperatures at the 49-Inch Elevation Using Two-Dimensional Core Model Compared to LOFT Data and ANF-RELAP Calculation

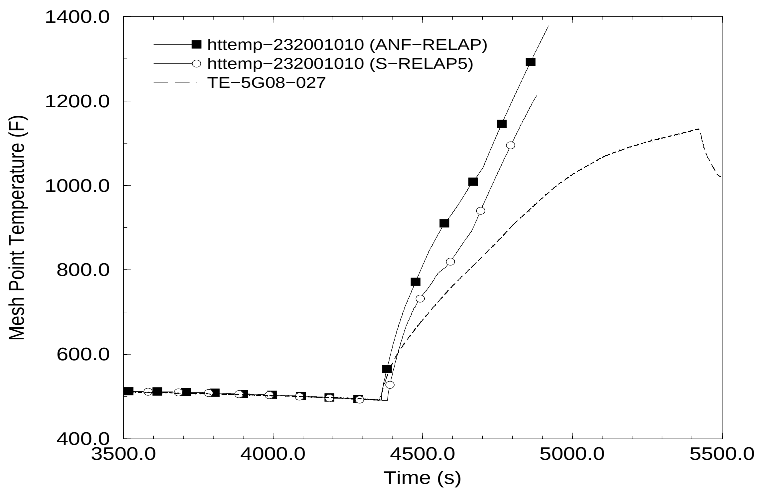


Figure 5.3.5 S-RELAP5 Clad Temperatures at the 28-Inch Elevation Using Two-Dimensional Core Model Compared to LOFT Data and ANF-RELAP Calculation

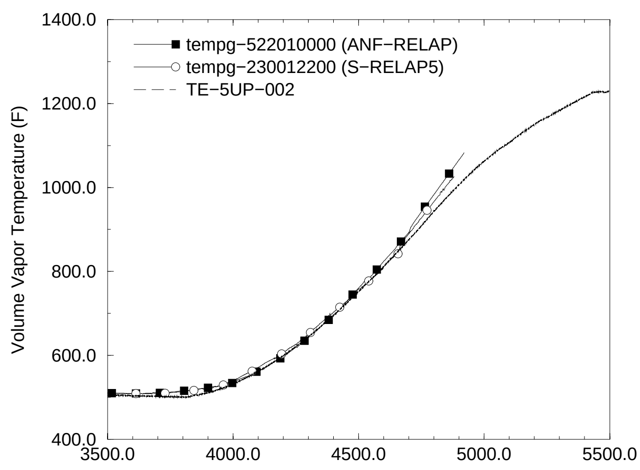


Figure 5.3.6 S-RELAP5 Steam Temperatures at the Core Exit Using Two-Dimensional Core Model Compared to LOFT Data and ANF-RELAP Calculation

5.4 *UPTF Loop Seal Clearing*

In 1991 Siemens performed (on a proprietary basis) the TRansient Accident Management (TRAM) test series A5 tests in the UPTF (References 7 and 27 through 29). This series consisted of full-scale integral and separate-effects tests, designed to evaluate loop seal behavior during a SBLOCA. The loop seal and pump configuration for the UPTF facility is similar to that for Westinghouse and Combustion Engineering PWRs. Separate-effect test (A5RUN11E) from this series was selected as the most appropriate test to evaluate the ability of S-RELAP5 to model this behavior.

Test A5RUN11E was one of two available UPTF tests with appropriate steam mass flow through the loop seal for SBLOCA and substantial steam superheat. After loop seal clearing, the steam flow through the loop seal is expected to be substantially superheated. The system pressure for this test, however, is lower than what is expected in a plant calculation. As a result, the steam is less dense with higher superficial velocities than expected in a SBLOCA plant calculation. These higher velocities should generate higher interfacial drag with the horizontally stratified liquid trapped in the loop seal and provide a bounding calculation.

5.4.1 Test Facility Description

UPTF is a full-scale PWR test facility designed to explore a number of thermal-hydraulic phenomena during various postulated accident scenarios. The facility consists of four separate loops with steam generator simulators and reactor coolant pump simulators, a reactor vessel with a core simulator, a containment simulator, and a variety of ECCS injection systems. Figure 5.4.1 is a schematic of the facility. The portion of the system relevant to the test used in this analysis consists of the piping from the second loop steam generator through the pump (including loop seal) and the cold-leg piping from the pump to the vessel downcomer. Figure 5.4.2 shows this portion of Loop 2 with selected key measurement instrumentation locations. The downcomer pressure measurement shown in Figure 5.4.2 (JAA01CP002L), actually is located at the outlet of the cold-leg for Loop 1, not at the outlet for Loop 2. Figure 5.4.3 shows the locations of important measurement instrumentation in the loop seal.

For test A5RUN11E, increasing the reactor coolant pump simulator resistance in the other three loops to infinity isolated the second loop. The system was pressurized to 320 kPa (46.4 psia) and filled with saturated steam. The vessel also was filled to 4 meters (13.12 ft) with saturated liquid. For the entire transient, the broken loop vent valve in the cool leg for Loop 4 was open to the containment simulator. System pressure was controlled by adjusting the containment pressure.

The test results are summarized in Figure 5.4.5 through Figure 5.4.9. At 2 seconds, steam injection into the containment simulator and system pressure control began. The system pressure control lowered the system pressure to about 310 kPa (45.0 psia) at about 30 seconds. At about 72 seconds, superheated steam injection into the steam generator in Loop 3 began. At the same time, slightly subcooled liquid water injection into the steam generator simulator side of the loop seal in Loop 2 began. The pressure controller allowed the system to pressurize to between 340 kPa and 350 kPa (49.3 and 50.8 psia) in response to the mass and energy addition to the system. Because the downcomer and core simulator were partially filled with liquid, steam injected into the steam generator simulator in Loop 3 was forced through the loop seal in Loop 2. During this period the loop seal in Loop 2 partially filled with liquid. [

]

At approximately 230 seconds, the liquid water injection into the loop seal was cut off and loop seal clearing began as steam was forced through the loop seal. At about 400 seconds the loop seal clearing test ended and the steam injection rate was ramped down. The liquid remaining in the loop seal then collapsed into the horizontal section. [

]

At about 470 seconds, liquid and steam injection began again. The steam injection rate was only about two-thirds of what it was for the first test. The pump side of the loop seal again filled to a collapsed level between 1.0 meter to 1.2 meters (3.28 and 3.94 ft) At about 625 seconds, the liquid water injection was stopped and the second loop seal clearing test began. At about 790 seconds, the second loop seal clearing test ended and the steam injection rate was reduced, allowing the liquid trapped in the loop seal to collapse into the horizontal section. [

]

5.4.2 S-RELAP5 Model Description

The S-RELAP5 model used for this analysis consists of the piping from the second loop steam generator simulator to the pump simulator (including the loop seal), the pump simulator, the cold-leg piping from the pump simulator to the vessel downcomer and the first downcomer volume. This analysis includes a sensitivity study on loop seal steam generator side nodalization and maximum time step. Two different nodalizations for the piping on the steam generator side of the loop seal were examined. [

]

5.4.3 Boundary Conditions

This analysis simulates only a portion of the larger UPTF system by specifying boundary conditions for the portion being modeled. The boundary conditions consist of inlet steam mass flow rate and temperature, injected water mass flow rate and temperature, and outlet (downcomer) pressure. Figure 5.4.5 through Figure 5.4.7 show the boundary conditions used to drive the S-RELAP5 simulation and the test data corresponding to these boundary conditions. The model was initialized at equilibrium as filled with saturated steam at a pressure of 320 kPa (46.4 psia).

5.4.4 Comparison to Data

Comparing the calculated levels and pressure drops (Figure 5.4.8 and Figure 5.4.9) demonstrates that the calculated loop seal clearing was similar to the data. [

]

The accurate liquid inventory in the loop seal is given by the data in the period immediately following each test, when the liquid collapses into the bottom of the loop seal. [

]

The second test had a lower steam mass flow rate and, as a consequence, more liquid remains trapped in the loop seal. The steam generator side level was approximately the same, but the pump side level was much higher. A significant amount of liquid, compared to the high flow test, was entrained in the pump simulator causing the high level and pressure drop in this test. [

]

The comparisons of S-RELAP5 predictions with test A5RUN11E data show S-RELAP5 predicts loop seal clearing adequately. It also predicts a larger amount of liquid remaining in the loop seal after clearing than was measured in the test and a higher differential pressure across the loop seal after clearing. In a PWR SBLOCA transient, the pressure drop across a cleared loop will affect the levels in the core and downcomer. As the pressure drop increases, the core level will decrease which can increase the PCT.

5.4.5 Sensitivities

In addition to benchmarking the base model to the measured data, sensitivity studies were performed to demonstrate the impact of the loop seal nodalization and the time step used in the calculation. [

] Figure 5.4.11 and Figure 5.4.12 compare the S-RELAP5 calculations with the data.

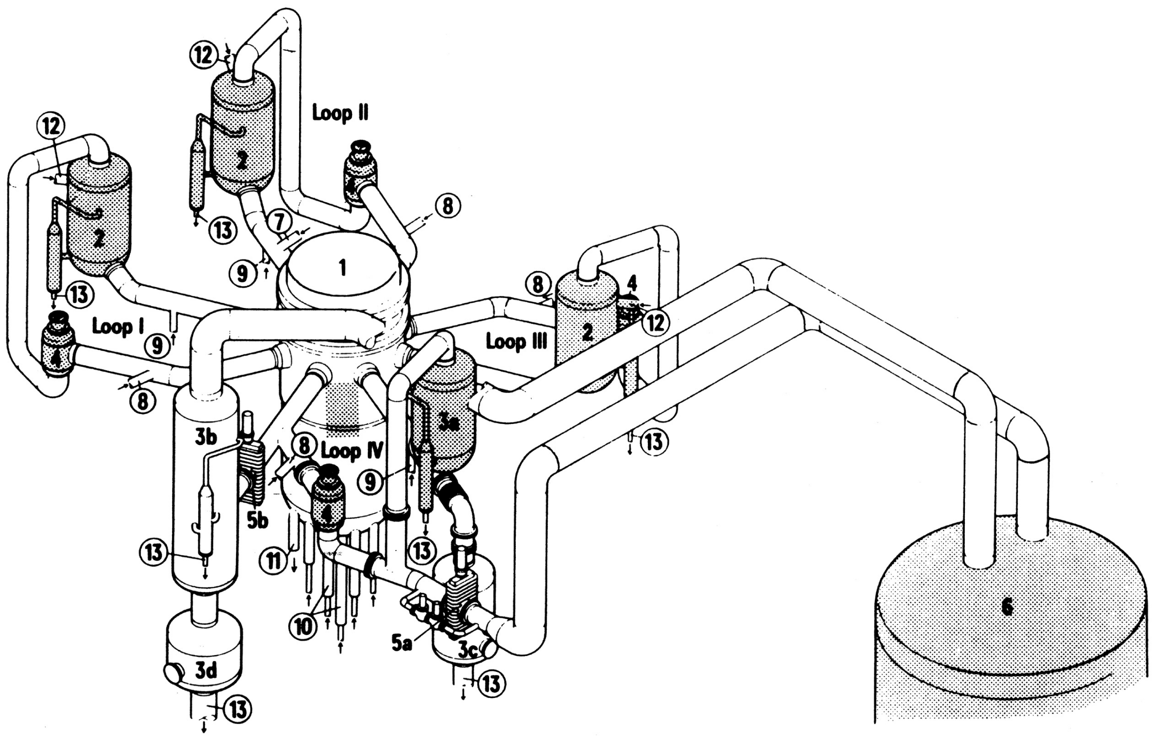
The sensitivity of the S-RELAP5 calculations to time step was evaluated with the base model. Maximum time steps of 100 ms, 10 ms and 5 ms were used. Figure 5.4.8, Figure 5.4.9, and Figure 5.4.13 through Figure 5.4.16 compare the collapsed level and pressure drop to the data.

The loop seal behavior is not particularly sensitive to changes in nodalization or to time step and is consistently conservative for the two nodalizations used.

5.4.6 Conclusions

The pressure drop across a loop seal and the quantity of liquid remaining in a loop seal after loop seal clearing from this test were compared to the predicted values for the test using S-RELAP5. The S-RELAP5 simulation of the loop seal was based on the SBLOCA modeling. Finally, different nodalizations and time steps were used to evaluate the sensitivity of the SBLOCA model to these modeling parameters.

Compared to the UPTF data, S-RELAP5 tends to predict a larger quantity of liquid in the loop seal in the post-clearing period. It also predicts a larger pressure drop. The predicted behavior was found to be relatively insensitive to time step size and to volume lengths. Both the larger quantity of liquid and larger pressure drop can cause higher PCTs to be calculated for SBLOCA analysis, hence is conservative.



1	Test Vessel
2	Steam Generator Simulator (Intact Loop)
3a	Steam Generator Simulator / Water Separator (Broken Loop Hot Leg)
3b	Water Separator (Broken Loop Cold Leg)
3c	Drainage Vessel for Hot Leg
3d	Drainage Vessel for Cold Leg
4	Pump Simulator
5a	Break Valve (Hot Leg)
5b	Break Valve (Cold Leg)
6	Containment Simulator
7	Surgeline-Nozzle
8	ECC-Injection Nozzles (Cold Leg)
9	ECC-Injection Nozzles (Hot Leg)
10	Core Simulator Injection Nozzle
11	TV-Drainage Nozzle
12	Steam Injection Nozzle
13	Drainage Nozzle

Simulator

Figure 5.4.1 Upper Plenum Test Facility

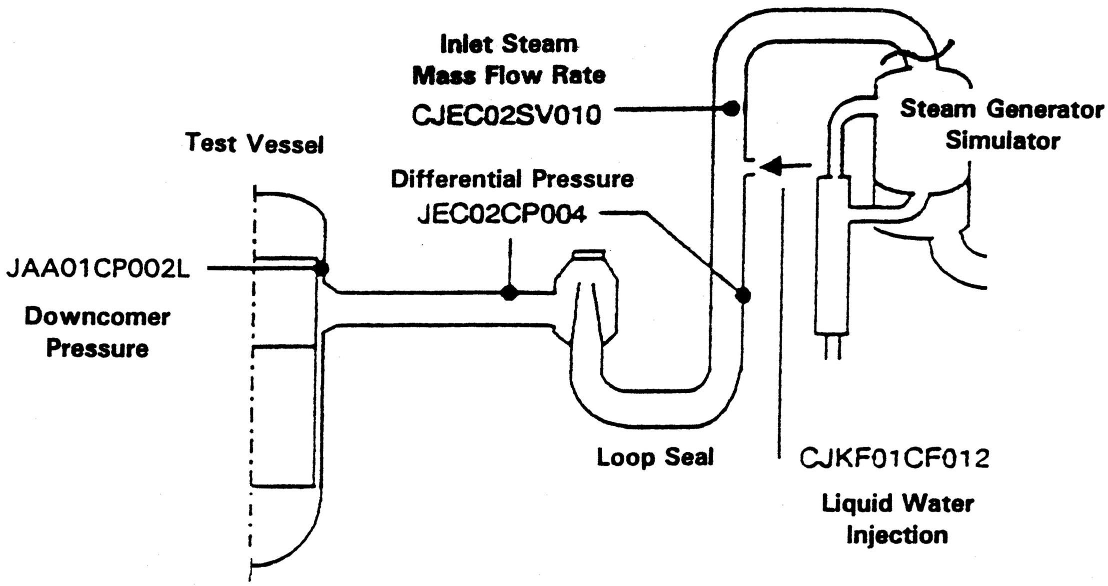


Figure 5.4.2 Configuration and Instrumentation for Loop 2

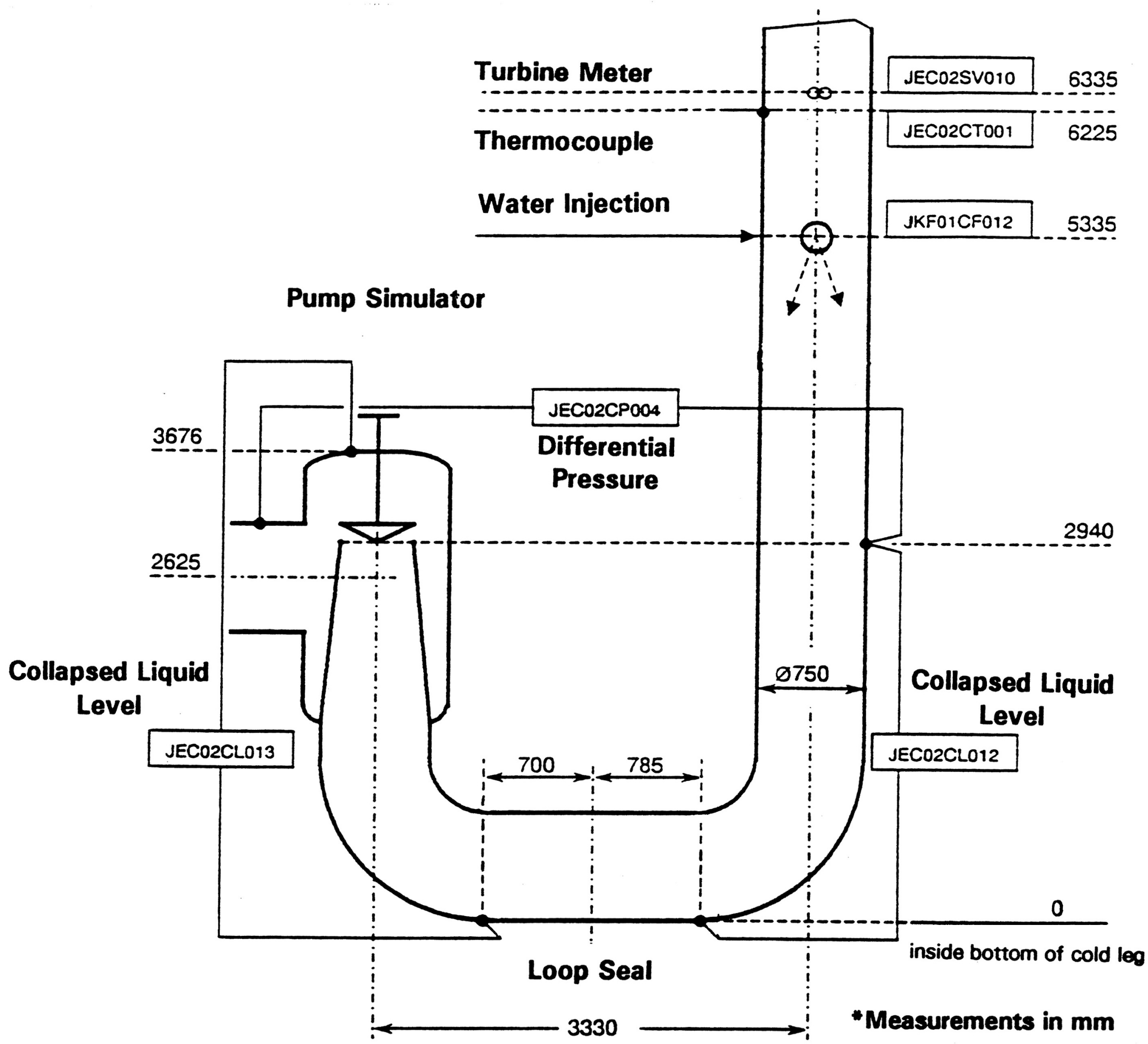


Figure 5.4.3 UPTF Loop 2 Loop Seal Configuration and Instrumentation

Figure 5.4.4 Loop Seal Nodalization with 13 Volumes

Figure 5.4.5 Cold-Leg Outlet Pressure Boundary Condition for S-RELAP5 Model UPTF Test A5RUN11E

Figure 5.4.6 Cross-Over Leg Inlet Steam and Water Injection Mass Flow Rate Boundary Conditions for S-RELAP5 Model UPTF Test A5RUN11E

Figure 5.4.7 Cross-Over Leg Inlet Steam and Water Injection Temperature Boundary Conditions for S-RELAP5 Model UPTF Test A5RUN11E

Figure 5.4.8 Comparison of Loop Seal Collapsed Liquid Level to Data from UPTF Test A5RUN11E-Base Model 10 ms Time Step

Figure 5.4.9 Comparison of Differential Pressure Across Loop Seal to Data from UPTF Test A5RUN11E-Base Model with 10 ms Time Step

Figure 5.4.10 Loop Seal Nodalization with 10 Volumes

Figure 5.4.11 Comparison of Loop Seal Collapsed Liquid Level to Data from UPTF Test A5RUN11E–Alternative Model with 10 ms Time Step

Figure 5.4.12 Comparison of Differential Pressure Across Loop Seal to Data from UPTF Test A5RUN11E–Alternative Model with 10 ms Time Step

Figure 5.4.13 Calculated Comparison of Loop Seal Collapsed Liquid Level to Data from UPTF Test A5RUN11E-Base Model with 100 ms Time Step

Figure 5.4.14 Comparison of Differential Pressure Across Loop Seal to Data from UPTF Test A5RUN11E-Base Model with 100 ms Time Step

Figure 5.4.15 Calculated Comparison of Loop Seal Collapsed Liquid Level to Data from UPTF Test A5RUN11E - Base Model with 5 ms Time Step

Figure 5.4.16 Comparison of Calculated Differential Pressure Across Loop Seal to Data from UPTF Test A5RUN11E - Base Model with 5 ms Time Step

5.5 *BETHSY*

Test 9.1b at the BETHSY test facility (Reference 30) is an integral benchmark test for SBLOCA analyses. It simulates the typical limiting break size and location in a PWR. This test simulates many of the major phenomena in SBLOCA transients in PWRs, such as loop seal clearing, core level depression, core heat up and refill, and break flow. It provides an extensive database for assessing the various thermal hydraulic models in system computer codes and has been designated as International Standard Problem (ISP) 27 for the international code assessment program (ICAP) community during the code development stage of RELAP5/MOD2 and RELAP5/MOD3 (References 31 and 32).

S-RELAP5 was used to simulate the phenomena, including primary and secondary system pressures, core collapsed level, integrated break flow mass, loop seal clearing, and ECCS injection.

5.5.1 Test Facility Description

BETHSY is a test facility designed to represent a 3-loop 2775-MWt Westinghouse-type PWR. It is scaled such that the heights are preserved and the volume is scaled by a factor of 1/100. The primary and secondary systems have design pressures of 17.2 (2495 psia) and 8 MPa (1160 psia) respectively. The core simulator has 428 full-length heater rods and 29 guide tubes. The heater rods simulate a 17x17 fuel design. Other components in the primary system include a core bypass, an external downcomer, three piping loops, reactor coolant pumps, and a pressurizer. The secondary system consists of three steam generators with 34 U-tubes each. The flow rates and temperatures for the main and auxiliary feedwater systems are adjustable.

The ECCS includes HHSIs, LHSIs, and accumulators. The ECCS water can be injected in the cold-legs or at other locations such as the hot-legs, the top of downcomer, or the lower and upper plena. In addition, trace heaters are installed in the primary coolant system and steam generators to compensate for the excessive heat loss due distorted ratio between volume and surface area.

Figure 5.5.1 shows the principal components of the BETHSY facility. Reference 30 describes the BETHSY facility in more detail.

5.5.2 S-RELAP5 Model

The S-RELAP5 input model used to simulate the BETHSY SBLOCA is based on a RELAP5/MOD3 model developed at INEEL (Reference 33). The input model was modified for use with S-RELAP5 and to incorporate SPC modeling guidelines for SBLOCA.

[

]

The schematic noding diagram is shown in Figure 5.5.2. The following specific features were incorporated in the S-RELAP5 model

[

2.

]

5.5.3 Boundary Conditions

The event was initiated by opening a 2-inch break located at the cold-leg centerline on the discharge side of the pump. HHSI was assumed to be unavailable, which ensured core uncovery and fuel rod heat up. When the cladding temperature reached 723 K (842 °F), an "ultimate procedure" was instituted that involved a steam generator dump to atmosphere to depressurize the primary system below the accumulator pressure and the shut-off head of the LHSI. The test was considered over when the reactor primary system was in a condition where the residual heat removal system could be actuated.

The power and pump speeds from the data were used as boundary conditions for the analysis. Figure 5.5.3 and Figure 5.5.4 show the core power versus time and pump speed versus time, respectively.

5.5.4 Comparison to Data

Table 5.5.1 compares the calculated and measured chronology of key events. The comparison demonstrates that S-RELAP5 can simulate the major phenomena of a SBLOCA transient in a PWR. The maximum clad temperature predicted by S-RELAP5 was 1035 K (1403 F), which is conservative compared to the measured value of 995 K (1331 °F). The calculated time of PCT was 3030 seconds, which agrees well with measured value of 3050 seconds.

Figure 5.5.5 through Figure 5.5.10 compare the predictions from S-RELAP5 with the data. The S-RELAP5 calculated results include a time shift to remove the 100 second steady state calculation performed before transient initiation. In general, the calculation results compare well with data.

Figure 5.5.5 compares calculated and measured pressure response for the primary system. The emptying of the pressurizer drives the initial, rapid depressurization. During the slow, quasi-steady pressure plateau extending to 2560 seconds, the pressure is the saturation pressure for the primary coolant. The pressure differences after about 750 seconds reflect the differences in the core exit temperature during this period. At about 2560 seconds, the ultimate procedure was initiated, which led to further depressurization.

Figure 5.5.6 compares calculated and measured pressure response for the secondary system. The calculation and data agree very well, except for the depression in the secondary pressure between 500 and 1500 seconds. This depression is caused by a loss of recirculation in the secondary side of the steam generators and the consequent subcooling in the risers (Reference 30). This is also the period where the break flow is considerably under-predicted.

Figure 5.5.7 compares calculated and measured break flow. The calculation did not predict the increase in break flow rate in the period between 500 and 1500 seconds. The subcooling in the risers caused a decreased temperature, and possibly a decreased void fraction, at the break during this period. These contributed to the increased mass flow from the break during the 500 to 1500 second time frame. After 1500 seconds, the measured break flow dropped considerably in magnitude, while the calculated mass flow was considerably larger from 1500 to 2000 seconds. Beyond 2000 seconds, the calculated flow decreased in magnitude until it coincided with the measured break flow at 2500 seconds. The initially under-predicted then over-predicted mass flows caused the loops seals to uncover later than measured, while the core uncovering and subsequent heat-up occurred slightly earlier than measured. Overall, the comparison with data is reasonable.

Figure 5.5.8 shows the loop seal clearing behavior by comparing calculated and measured differential pressure on the descending leg of Loop 2. The behavior before the 2560 seconds (ultimate procedure) shows two major aspects of loop seal behavior. The first is the rapid drop when loop seal clearing occurred. While the drop is significant, it does not reduce to zero. As liquid falls back in to the loop seal, a pressure differential of from 5 to 10 kPa (0.7 to 1.5 psia) remains. As the liquid clears the loop, the pressure differential finally drops to zero. In the uncleared loops, the pressure differential of 10 kPa (1.5 psia) remains until the ultimate procedure begins. S-RELAP5 predicts a later loop seal clearing than was observed. This is consistent with the break flow rates, because the break uncovers when the loop seal clears. The post-clearing behavior for this case, while delayed reflects the data quite well.

Figure 5.5.9 compares calculated and measured collapsed core level. This particular comparison is one of the critical comparisons for the SBLOCA outcome. The calculated level agrees very well with data, both qualitatively and quantitatively.

Figure 5.5.10 compares calculated and measured clad temperatures at the PCT node. The calculated results reflect the slightly early, deeper collapsed level response for S-RELAP5 compared to the data. The calculated PCT was about 1035 K (1403 °F), as compared to the measure value of 995 K (1331 °F). The calculated time of PCT was 3030 seconds compared to the measure time of 3050 seconds.

5.5.5 Conclusions

The S-RELAP5 code was assessed against the BETHSY Test 9.1b (ISP 27). S-RELAP5 simulates the various observed major phenomena well, including primary and secondary system pressures, core collapsed level, break flow, loop seal clearing, and ECCS injection. [

] S-RELAP5 was shown to closely predict the loop seal clearing process and the post-clearing behavior observed in the test. Finally, the maximum clad temperature was conservatively predicted to be about 1035 K (1403 °F) as compared to data of 995 K (1331 °F). The calculated PCT time of occurrence was 3030 seconds which agrees well with data of 3050 seconds. Therefore, the present results support the use of S-RELAP5 for PWR SBLOCA analyses.

Table 5.5.1 Chronology of Main Events

Event	Event Time, s Measured	Event Time, s Calculated
Transient starts	0	0
Scram signal occurs	41	33
Pressurizer empties	50	48
Safety injection signal generated (P = 11.9 M Pa)	54	50
Core power decay starts 17 seconds after scram signal	58	50
Aux. feedwater starts (30 seconds after SI signal)	82	80
Pump coastdown starts 300 seconds after SI signal	356	350
Pump stops	971	970
First core exposure begins	1830	2000
First loop seal clears in Loop 2	1944	2150
Ultimate Procedure Starts	2562	2562
Loop seal reforms in Loop 2	2750	2650
Accumulator injection starts	2962	2915
Second loop seal clears in Loop 2	3040	3045
Second loop seal reforms in Loop 2	3680	3800
Accumulator isolates	3831	3900
LHSI starts	5177	5154

Table 5.5.2 Initial Conditions for BETHSY Test 9.1b

Parameter	Units	Measured
PRIMARY LOOP		
Core differential temperature	K	3.58
Primary pressure	MPa	15.51 ± 0.09
Core inlet temperature	K	559.85 ± 0.5
Primary loop flow rate	kg/s	50.0 ± 5
Pump rotational speed	rpm	2940 ± 30
Core power	kW	2857 ± 30
Pressurizer pressure	MPa	15.51 ± 0.09
Pressurizer level	m	4.08 ± 0.1
Primary mass inventory	kg	1960
SECONDARY SYSTEM		
Steam dome pressure	MPa	6.91 ± 0.04
Feedwater flow rate/SG	kg/s	0.52
Downcomer level	m	13.45 ± 0.05
Recirculation ratio/SG	-	20 ± 2
Secondary mass inventory/SG	kg	820 ± 30
EMERGENCY CORE COOLING		
Accumulator pressure	MPa	4.18 ± 0.04
Accumulator temperature	K	290.15 ± 1
Accumulator liquid volume	m^3	0.286
EXTERNAL CIRCUITS		
Trace heating	kW	107.5 ± 2
Pump connected cooling circuits	kW	25 per pump

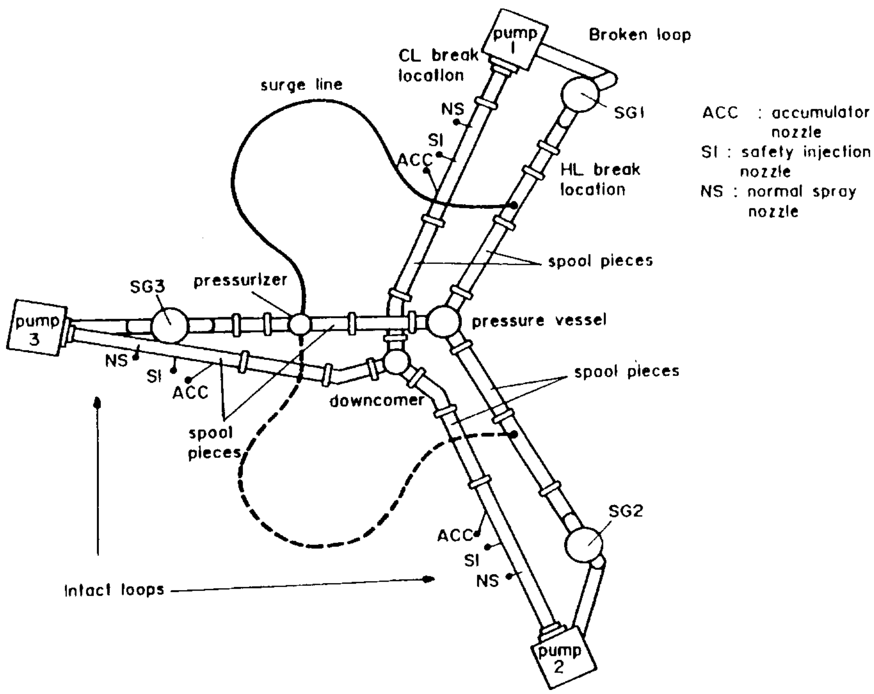


Figure 5.5.1 Schematic of BETHSY 3-Loop Configuration

Figure 5.5.2 S-RELAP5 Nodalization of BETHSY Facility

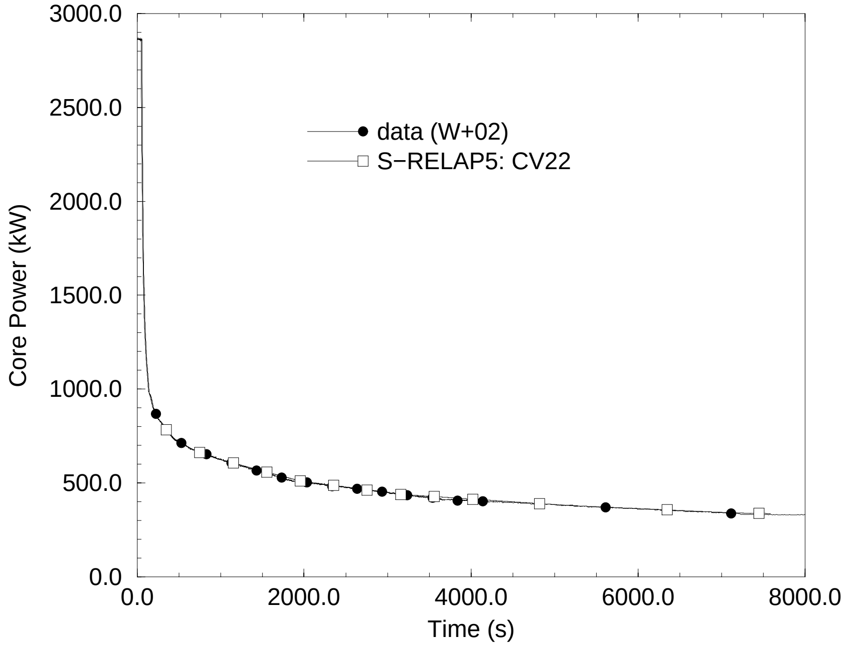


Figure 5.5.3 S-RELAP5 Core Power Compared to Experimental Data

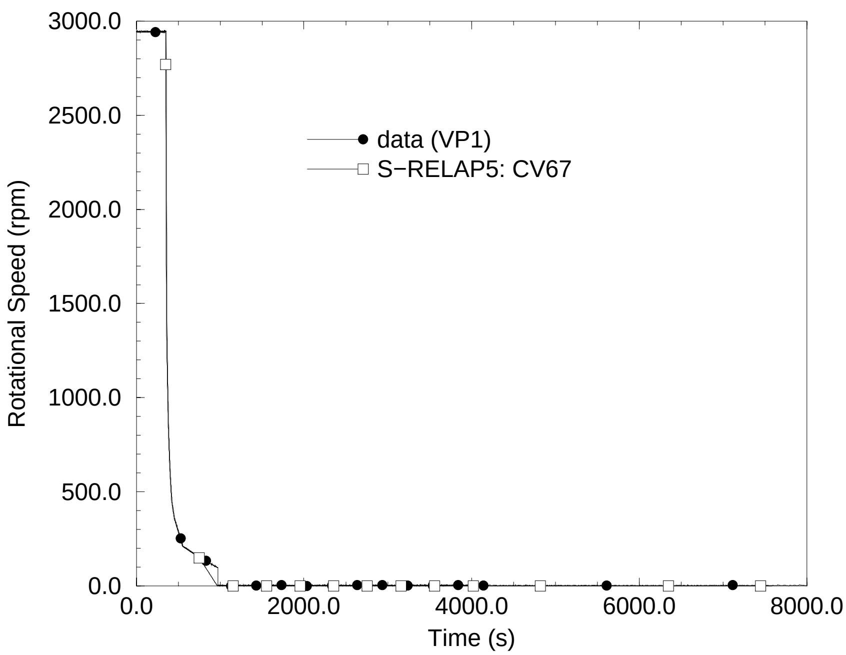


Figure 5.5.4 S-RELAP5 Pump Speed Compared to Experimental Data

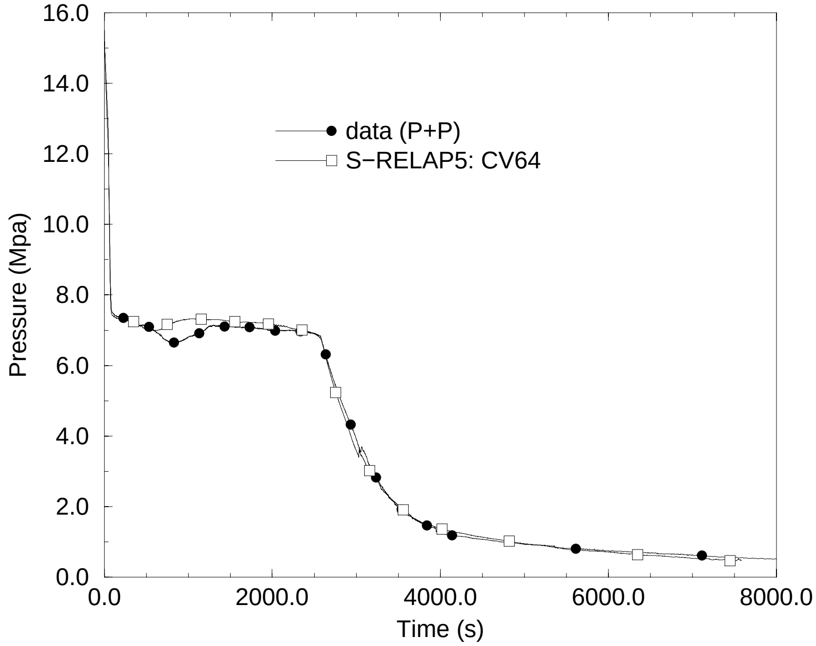


Figure 5.5.5 S-RELAP5 Pressurizer Pressure Compared to Experimental Data

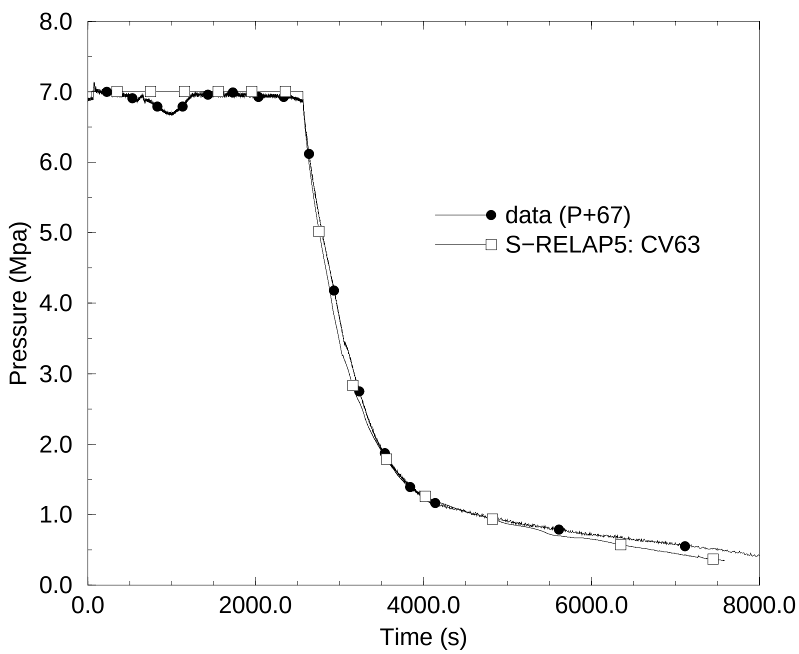


Figure 5.5.6 S-RELAP5 Secondary Pressures Compared to Experimental Data

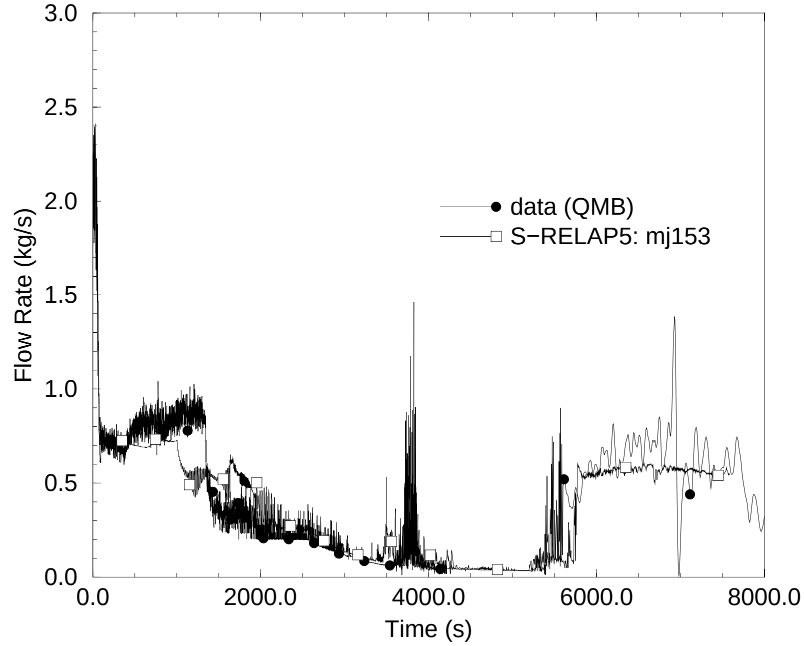


Figure 5.5.7 S-RELAP5 Break Flow Compared to Experimental Data

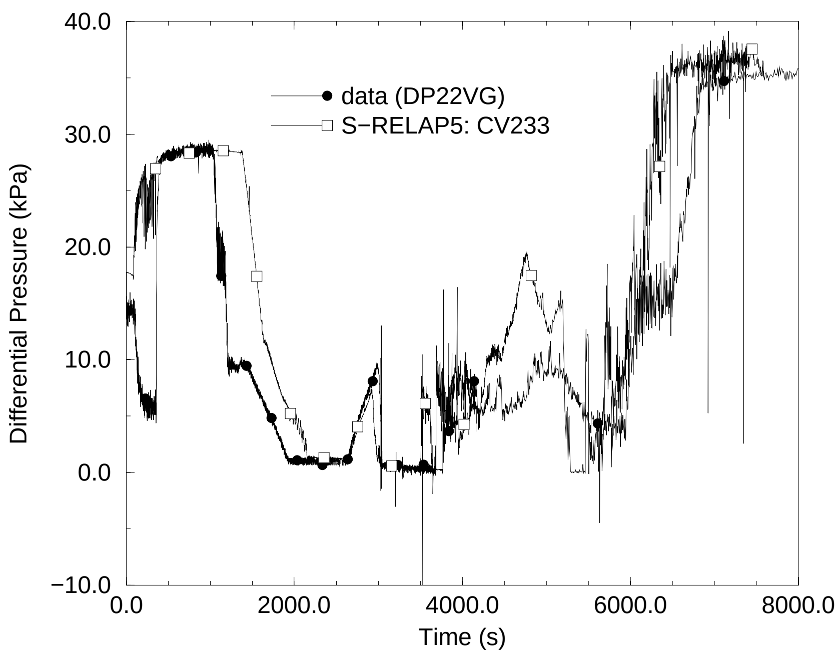


Figure 5.5.8 S-RELAP5 Loop Seal Downflow Side Differential Pressure Compared to Experimental Data from Loop 2

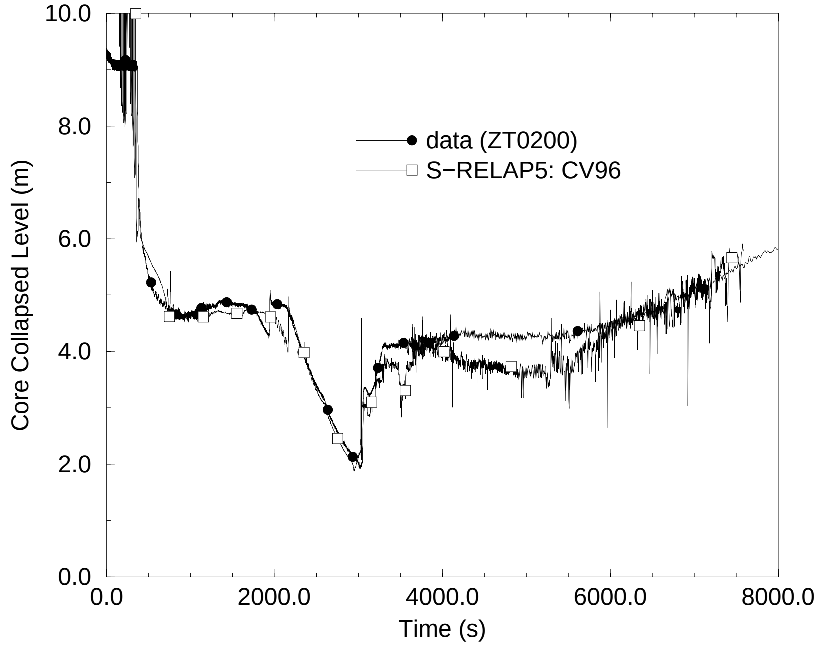


Figure 5.5.9 S-RELAP5 Core Collapsed Level Compared to Experimental Data

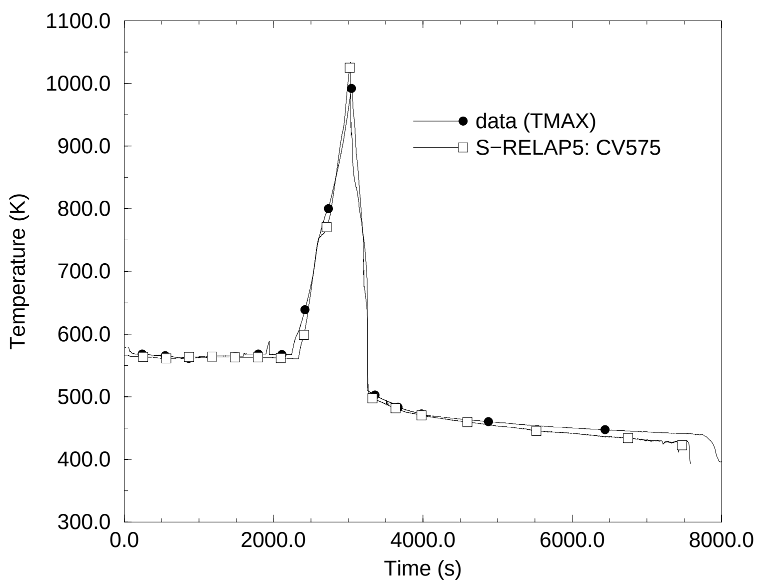


Figure 5.5.10 S-RELAP5 Maximum Clad Temperature Compared to Experimental Data

6.0 Methodology Example

The example calculation is presented which shows the application of the S-RELAP5 SBLOCA methodology to a 2300-MWt, Westinghouse-designed PWR with 3 hot-legs, 3 cold-legs, and 3 vertical U-tube steam generators. The reactor vessel contains a downcomer, upper and lower plena, and a reactor core containing 157 fuel assemblies. The hot-legs connect the reactor vessel with the vertical U-tube steam generators. Feedwater is injected into the downcomer of each steam generator. There are three auxiliary feedwater pumps (AFW); two motor driven and one turbine driven. The ECCS contains three HHSI pumps, three accumulators, and two LHSI pumps.

6.1 *S-RELAP5 Model*

The reactor coolant system of the plant is nodalized in the S-RELAP5 model into control volumes interconnected by flow paths. The model includes 3 accumulators, a pressurizer, and three steam generators with both primary and secondary sides modeled. All the loops were modeled explicitly to provide an accurate representation of the plant.

Figure 6.1 and Figure 6.2 are nodalization diagrams for the primary and secondary systems.

Decay heat was determined from reactor kinetics equations with actinide and decay heating as prescribed by Appendix K.

The calculations assumed loss of off-site power concurrent with reactor scram. The single failure criterion required by Appendix K was satisfied by assuming the loss of one diesel generator, which resulted in the disabling of one HHSI pump, one LHSI pump, and one motor-driven auxiliary feedwater pump. In addition, one HHSI pump was assumed to be off line for service, leaving only one active HHSI pump. Initiation of the HHSI system was delayed the maximum expected value beyond the time of SIAS to account for the time required for startup of the diesel generator, switching, and valve sequencing. The disabling of a motor-driven auxiliary feedwater pump left one motor-driven pump and the turbine-driven pump available. The motor-driven pump actuation setpoint was based on low steam generator level plus a delay. No credit was taken for the turbine-driven AFW.

In the analysis, the RCPs tripped at reactor scram, coincident with the loss of off-site power. Steam generator tube plugging was set to 6% symmetrically.

The axial power shape used was a conservatively top-skewed (EOC) shape. The power in the hot rod was at the technical specification peaking limits.

[

]

The limiting case was identified via a break spectrum analysis.

6.2 *Break Spectrum*

A range of break sizes was analyzed for breaks located in the pump discharge cold-leg as a part of the sample problem. These included 1.5-inch, 2.0-inch, and 2.5-inch-diameter breaks. The 2.0-inch break produced the limiting PCT (Table 6.1).

The 1.5-inch break was small enough that HHSI flow was sufficient to prevent any significant core uncovery. The primary system lost mass for the first 6000 seconds, then began recovering. Core uncovery began at about 4800 seconds and a brief core heatup occurred in the 5000 to 7200 second period. The HHSI flow exceeded the boil-off rate and the core re-covered. At the end of the simulation, the primary system was gaining mass at the rate of about 1 lbm/s and the vessel downcomer was filled to the cold-leg nozzle elevation.

The 2.5-inch break was large enough to cause the system to depressurize to the accumulators injection pressure fairly rapidly. Although uncovery occurred much sooner, the amount of time spent uncovered was relatively short. The large amount of liquid injected by the accumulators between 1800 and 2500 seconds terminated the core heatup. When the calculation was terminated only about 10% of the accumulators' inventory had been injected.

The 2.0-inch break was the limiting break. The core uncovery was delayed compared to the 2.5-inch break, but the rate of depressurization to the accumulator setpoint was much lower and the amount of time the hot rod spent uncovered was greater.

6.3 *2-Inch Break Base Case*

The sequence of events for this case is presented in Table 6.2. The 2-inch break caused a longer period of core uncovery than the 1.5-inch and 2.5-inch breaks. Cladding temperatures rose steadily during the 1100 seconds between core uncovery and accumulator injection. The calculation was terminated at 3500 seconds.

The break flow is plotted in Figure 6.3. The break flow is driven by the system pressure and the void at the break. Until loop seal clearing occurs, it mirrors the primary pressure. At that time, the flow transitions from liquid to steam and the mass flow out the break drops precipitously (see Figure 6.4).

Figure 6.5 shows the pressure traces for the PCS and the three steam generators. The behavior is typical of limiting SBLOCA events. The primary pressure drops rapidly to saturation, then again falls rapidly as the core level drops and the boil-off rate decreases.

Figure 6.6 shows the voids in the ascending legs of the loop seals. [

] only one loop cleared (Loop 1) at 1184 seconds.

After the initial clearing, the loop seal experienced some carryover of liquid from the horizontal segment of the seal for a period, then re-cleared.

Figure 6.7 shows the combined HHSI flow for this case. As the system depressurizes because of the core boil-off, the HHSI flow increases.

The core collapsed level and core mixture levels are shown in Figure 6.8. The difference between the two shows the presence of two-phase flow in the core. The uncovery of the core at about 1900 seconds is clearly shown.

Figure 6.9 shows the cladding and vapor temperatures corresponding to the node with the maximum PCT of 1634 °F. The core is heating until the accumulator injects at 3080 seconds. The temperature then begins to recover to saturation.

With the core flooded, the boil-off rate and the system pressure rise. The pressure rise reduces HHSI flow, and if the pressure rises sufficiently, the accumulator flow will cease. Eventually, a second heat-up will occur. However, at this later time the decay heat will be lower and the temperature excursion will be far smaller.

6.4 *Sensitivity Studies*

The sensitivity studies described in this section address a set of variations expected to have little effect on the outcome. The figure of merit for the sensitivity studies is the difference in PCT between a designated base case and the resulting sensitivity case. The results of the sensitivity study are reported and summarized in Table 6.3. In all cases expected to have minimal impact, the change in PCT is 5 °F or less. This reflects a stable, converged methodology.

6.4.1 Time Step Size

The nominal time step size recommended for transient calculations is 0.01 seconds. For the sensitivity case, the maximum time-step size was halved to 0.005 seconds. The run started from the same steady-state as the original run. [

]

6.4.2 Restart

Sensitivity studies were conducted to show the sensitivity of PCTs to the choice of steady-state restart number and to restarting a transient. Neither of these changes will have a significant effect on the results.

The first sensitivity run was conducted by rerunning the 2-inch break simulation and restarting from 600 seconds of steady-state rather than 300 seconds of steady state. [

]

The second sensitivity run restarted the base calculation at 1000 seconds (200 seconds before loop seal clearing) and rerunning the 1000 – 3500-second part of the simulation. [

]

6.4.3 Loop Seal [ ]

[

]

6.4.4 Pump Model

[

]

6.4.5 Radial Flow Form Loss Coefficients

This study was performed to show insensitivity of core radial flow loss coefficients on the outcome of the SBLOCA event. [

] These results show that the PCT calculated is insensitive to form loss in the horizontal direction. Therefore, form loss sensitivity studies are not required as part of the SBLOCA licensing analysis.

6.4.6 Nodalization Studies

Three nodalization studies were performed to test model performance. A simple test was to renumber connections between the cold legs and downcomer. The PCT calculated by S-RELAP5 should be insensitive to how the components are numbered in the model. The net change in calculated PCT was 0 °F (no change).

[

]

6.4.7 Summary

A sample analysis to determine the limiting break size was made by applying the revised SBLOCA methodology to a three-loop Westinghouse PWR. RODEX2 was used to determine fuel burn-up conditions at EOC. S-RELAP5 was used to calculate the maximum hot rod temperature. The results of the study showed that the 2 inch break case was limiting with a PCT of 1634 °F.

Furthermore, sensitivity studies were performed using the three-loop Westinghouse PWR to show that the solution was converged with respect to time step size, restart application, loop seal biasing, pump application, core radial flow, and nodalization. Results of the study show that the S-RELAP5-based SBLOCA methodology is well converged and has a very small sensitivity to all the parameters investigated. Therefore, the requirement to perform sensitivity calculations in licensing analysis is unnecessary.

Table 6.1 Break Spectrum Results Summary

Break Size (diameter in inches)	PCT (°F)
1.5	940
2.0 (base 2.0-inch case)	1634
2.5	1491

Table 6.2 Event Sequence for 2.0-Inch Break

Event	Time (s)
Break initiation	0.0
Reactor and RCP trip (505, 515)	38
SIAS trip (trip 509). 28.5s must elapse to get pumps on-line	63
HHSI began (trip 560)	217
Motor-driven AFW initiation (trip 1615)	111
Loop seal clearing – Loop 1 (Void 226-8 >0.97),	1184
Loop seal clearing – Loop 2 (component 326),	---
Loop seal clearing – Loop 3 (component 426 - broken leg),	---
Break uncovery (junction 885) (trip 568)	1277
Accumulator injection (trip 562)	3080
PCT occurs (1646 °F, H.S. 1721, node 28)	3084
Steam generator level recovered (trip 1611)	-
End of calculation	3500

Table 6.3 Sensitivity Studies

Figure 6.1 S-RELAP5 Primary System Nodalization

Figure 6.2 S-RELAP5 Secondary Side Nodalization

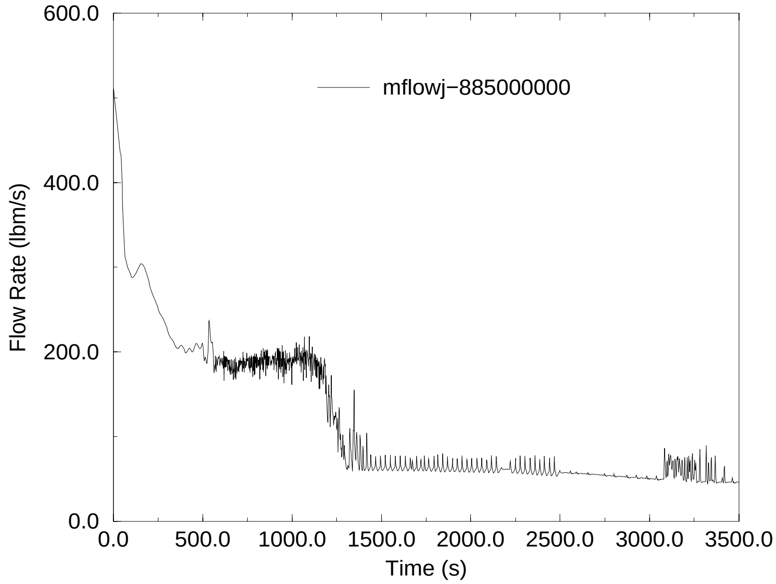


Figure 6.3 Break Flow Rate for 2.0-Inch Break

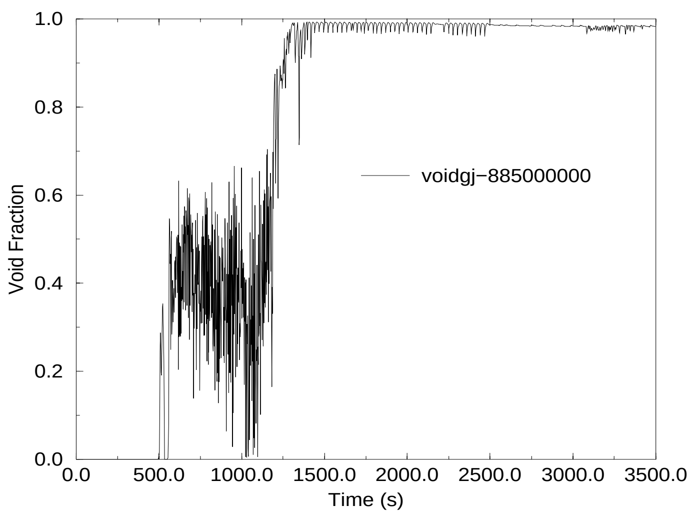


Figure 6.4 Break Void Fraction for 2.0-Inch Break

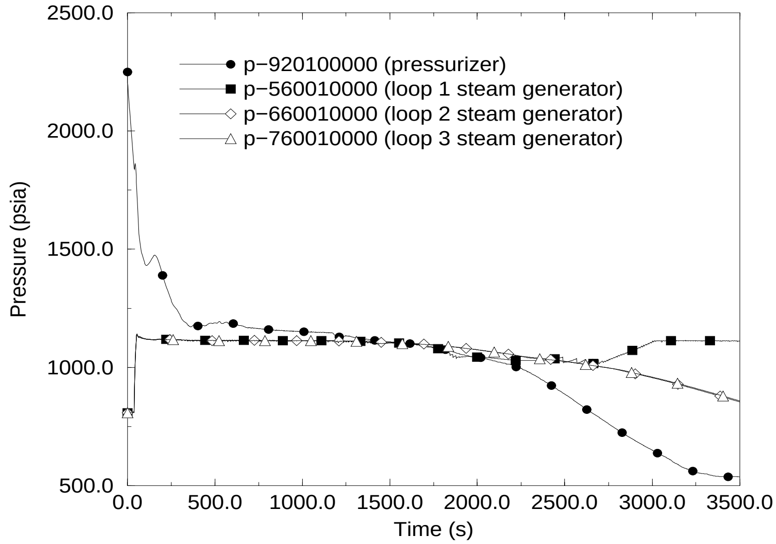


Figure 6.5 System Pressures for 2.0-Inch Break

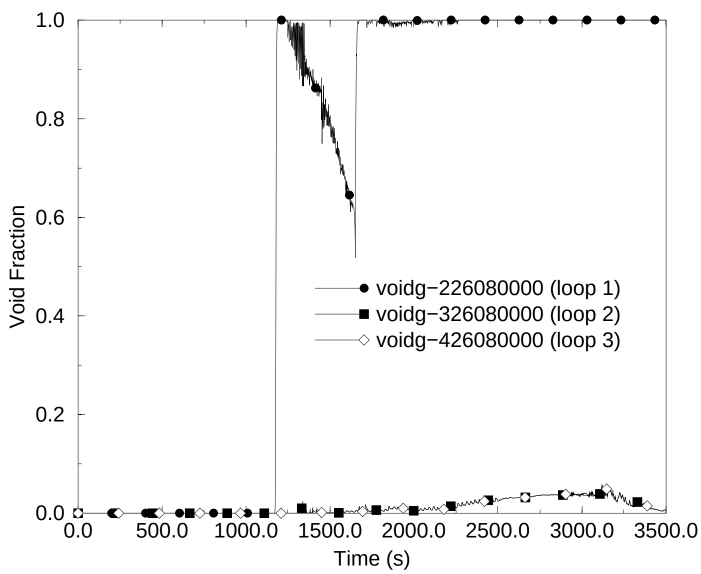


Figure 6.6 Loop Seal Void Fractions for 2.0-Inch Break

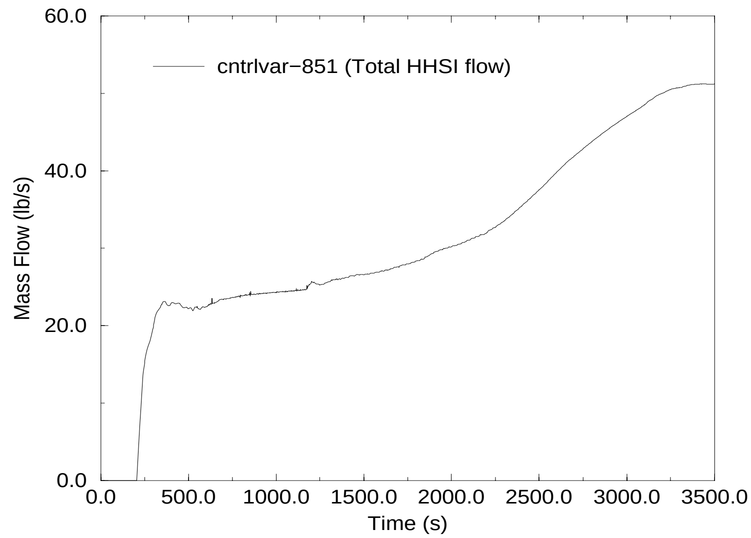


Figure 6.7 Combined High Head and Charging Flow for 2.0-Inch Break

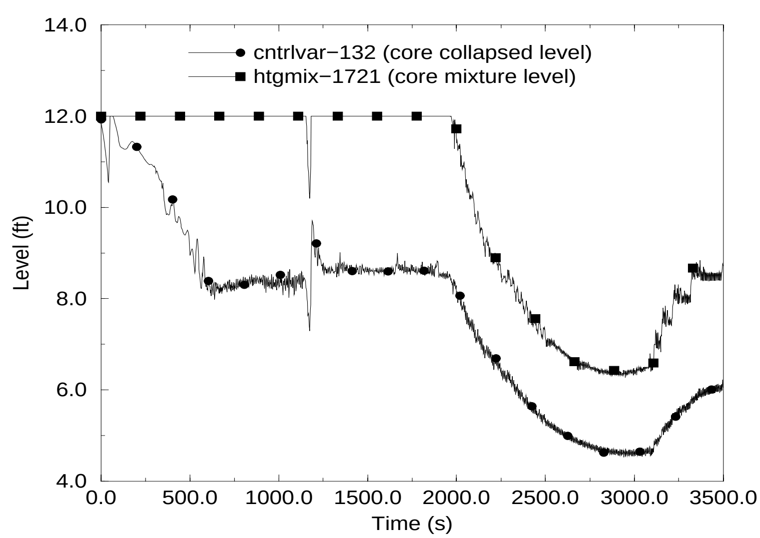


Figure 6.8 Core Mixture Level and Collapsed Liquid Level for 2.0-Inch Break

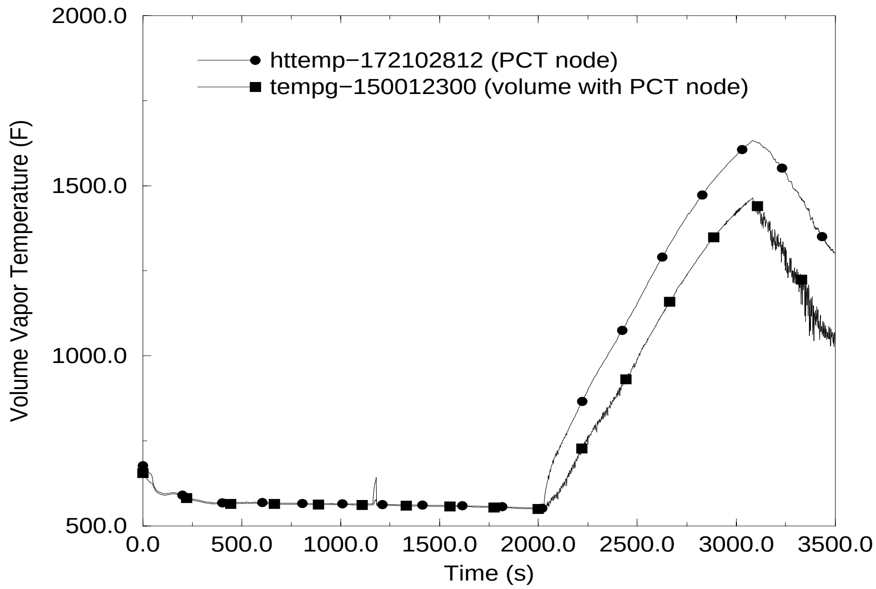


Figure 6.9 Vapor and Clad Temperatures for Hot Node with 2.0-Inch Break

7.0 References

1. XN-NF-82-49 (P) (A), Revision 1 Supplement 1 *Exxon Nuclear Company Evaluation Model Revised EXEM PWR Small Break Model,* Siemens Power Corporation, December 1994.

2. EMF-2100(P) Revision 1, *S-RELAP5 Models and Correlations Code Manual*, Siemens Power Corporation, December 1999.

3. XN-NF-81-58(P) (A), Supplements 1 and 2, Revision 2, *RODEX2 Fuel Thermal-Mechanical Response Evaluation Model*, Exxon Nuclear Company, March 1984.

4. ANF-81-58(P)(A) Revision 2 Supplements 3 and 4, *RODEX2 Fuel Thermal-Mechanical Response Evaluation Model*, Advanced Nuclear Fuels Corporation, June 1990.

5. XN-NF-82-07(P)(A), Revision 1, *Exxon Nuclear Company ECCS Cladding Swelling and Rupture Model*, Exxon Nuclear Company, November 1982.

6. S. M. Bajorek, A. Ginsberg, D. J. Shimeck, K. Ohkawa, M. Y. Young, L. E. Hochreiter, P. Griffin, Y. Hassan, T. Fernandez, D. Speyer, “Small Break Loss of Coolant Accident Phenomena Identification and Ranking Table (PIRT) for Westinghouse Pressurized Water Reactors”, Ninth International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-9), San Francisco, California, October 3-8, 1999.

7. “UPTF-TRAM Versuch A5, Freiblasen des Pumpenbogens Einzeleffekt- und Integralversuche, Quick Look Report,” NT33/94/011, Siemens AG, Erlangen, Germany, Power Generation Group (KWU), December 1994.

8. V. H. Ransom, *RELAP5/MOD2 Code Manual, Vol. 1: Code Structure, Systems Models, and Solution Methods*, NUREG/CR-4312, EGG-2396, Rev. 1, March 1987.

9. The RELAP5 Development Team of INEL, *RELAP5/MOD3 Code Manual, Vol. 1: Code Structure, Systems Models, and Solution Methods*, NUREG/CR-5535, INEL-95/0174, August, 1995.

10. 2D/3D Program Upper Plenum Test Facility, *UPTF Test No.6 Downcomer Countercurrent Flow Test,* Quick Look Report, U9 316/89/2, Siemens KWU March 1989; *UPTF Test No.7 Downcomer Countercurrent Flow Test,* Quick Look Report, E314/90/003, Siemens KWU, March 1990.

11. A. K. Jain, “Accurate Explicit Equation for Friction Factor,” *ASCE J. Hydraulics Div.*, 102, pp. 674-677, 1976.

12. R. T. Lahey, Jr., “A Mechanistic Subcooled Boiling Model,” *Proceedings of Sixth International Heat Transfer Conference,* Volume 1, pp. 293-297, 1978.

13. M. J. Thurgood, *Recommendation for Determining the Uncertainty in the Peak Clad Temperature Calculated by RELAP5/MOD2/ANF for a Loss-of-Coolant Accident*, NAI Report.

14. F. J. Moody, “Maximum Flow Rate of a Single Component, Two-Phase Mixture,” *Journal of Heat Transfer, Trans. ASME*, 87, pp. 134-142, 1965.

15. S. G. Bankoff, R. S. Tankin, M. C. Yuen, and C. L. Hsieh, “Countercurrent Flow of Air/Water and Steam/Water Through a Horizontal Perforated Plate,” *International Journal of Heat and Mass Transfer*, Vol. 24, pp. 1381-1395, 1981.

16. The RELAP5 Development Team of INEL, *RELAP5/MOD3 Code Manual Vol. 4: Models and Correlations,* NUREG/CR-5535, INEL-95/0174, August, 1995.

17. *Pump Two-Phase Performance Program*, EPRI NP-15556, Vols. 1-8, September 1980.

18. L. Baker and L. C. Just, *Studies of Metal-Water Reactions at High Temperature: III. Experimental and Theoretical Studies of Zirconium-Water Reaction*, ANL-6548, 1962.

19. C. W. Stewart, , et al, *VIPRE Code Manual: Volume 3, Programmer’s Manual*, Battelle Pacific Northwest Laboratory, June 1981.

20. H. Chelemer, P. T. Chu & L. E. Hochreiter, *THINC-IV – An Improved Program for Thermal-Hydraulic Analysis of Rod Bundle Cores*, WCAP 7956, Westinghouse Electric Corporation, June 1973.

21. E. Weiss, R. A. Markley & A. Battacharyya, “Open Duct Cooling-Concept for the Radial Blanket Region of a Fast Breeder Reactor,” *Nuclear Engineering and Design, Volume 16*, PP 175-386, 1971.

22. I. E. I’Delchik, et al, *Handbook of Hydraulic Resistance*, Second Edition, Revised and Augmented.

23. *Vessel Coolant Mass Depletion During a Small-Break LOCA*, EGG-SEMI-6010, Sept. 1982.

24. *Experimental Analysis and Summary Report on OECD LOFT Experiment LP-SB-3*, OECD LOFT-T-3905, December 1985.

25. D. L. Reeder, LOFT System and Test Description (5.5 ft Nuclear Core 1 LOCES, NUREG/CR-0247, TREE-1208, July 1978.

26. *Quick Look Report on OECD LOF Experiment LP-SB-03*, OECD LOFT-T-3604, March 1984.

27. “Freiblasen Des Pumpenbogens Einzeleffekt- und Integralversuche, Versuchsdatenbericht,” S554/93/007, Siemens AG, Erlangen, Germany, Power Generation Group (KWU), September 1993.

28. “UPTF-TRAM Test Group A Test Results, Analysis,” *Working Group of Experts Meeting*, Mannheim, Germany, Siemens AG, December 6-8, 1993.

29. “UPTF-TRAM Test Instrumentation, Measurement System Identification, Engineering Units and Computed Parameters,” S554/92/013, Siemens AG, Erlangen, Germany, Power Generation Group (KWU), November 1992

30. P. Clement, Chataing, T., and Deruaz, R., “Final Comparison Report for International Standard Problem 27,” French original report on BETHSY Test 9.1b.

31. S. Lee, B. D. Chung, and H. J. Kim, “Assessment of BETHSY Test 9.1b Using RELAP5/MOD3,” NUREG/IA-0103, June 1993. Korea’s ICAP report on BETHSY Test 9.1b

32. P. A. Roth, C. J. Choi, and R. R. Schultz, *Analysis of Two Small Break Loss-of-Coolant Experiments in the BETHSY Facility Using RELAP5/MOD3*, EGG-NE-10353, Idaho National Engineering Laboratory, July 1992.

33. Transmittal package from Carolee McKenzie (INEEL) to W. S. Yeung “FIN A6102 – Transmittal of ISP 26 and ISP 27 Data – CCK-03-94,” dated May 13, 1994. Package included data tapes, work books, and input decks for ISP26 and ISP27.

34. M. Jakob, “Heat Transfer and Flow Resistance in Cross Flow of Gases Over Tube Banks,” *Trans. ASME*, Vol. 60, pp 384-386, 1938.

Appendix A Core Radial Loss Coefficient Development

[

]

Distribution

J. S. Holm, 26/USNRC (12)

e-mail notification only
DM Brown
KE Carlson
H Chow
RE Collingham
RL Feuerbacher
KR Greene
RC Gottula
RG Grummer
TM Howe
SE Jensen
AB Meginnis
WT Nutt
LD O'Dell
PWR Neutronics
PWR Safety Analysis